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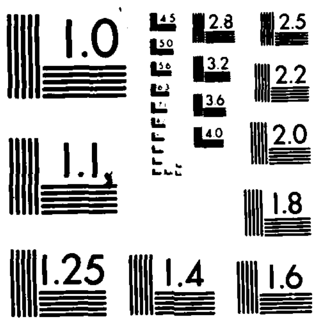

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METRIC CONVERSION FACTORS

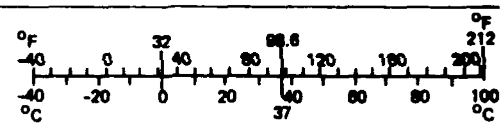
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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The economics of thermal energy recovery in jet engine test cells is examined. A numerical model to simulate the test cell augmenter tube is developed. This model is employed to determine the feasibility of installing heat exchangers along the augmenter or at the augmenter exit and using these heat exchangers to generate steam or electricity from the thermal energy in the jet exhaust.

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20. Continued

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INTRODUCTION

The energy in the exhaust of a jet engine is immense. To illustrate, with an assumption of only a 25% conversion efficiency, the thermal energy in the exhaust of a J79 engine running at intermediate power is tantamount to the energy required to generate about 280,000 lb/hr of 150-psi steam. To provide a perspective for this magnitude: the average peak steam consumption of the entire Naval Air Station (NAS), Miramar, Calif., on a winter day, is about 35,000 lb/hr.

New jet engines and engines undergoing maintenance or repair are examined in test cells* prior to operational use. In these test facilities, the jet energy is "wasted"; the jet exhaust is diluted and discharged to the atmosphere. Yet, test cells, by their confining geometry, provide an opportunity and, if waterwalls are installed or if heat exchangers are located somewhere in the path of the jet, possibly a means of obtaining part of a vast energy supply.

Operation of Test Cells

Jet engine test facilities have multiple functions: to supply a clean, distortion-free airflow to the engine inlet; to attenuate noise and chemical pollution by the jet; to decrease the kinetic energy of the jet exhaust; and to cool the exhaust sufficiently before dumping either to the atmosphere or to acoustical or environmental treatments.

Although the physics of test cells is extremely complex, their concept is simple; the jet exhaust entrains the cooler surrounding air, losing its energy to this secondary flow, which it carries along through the augmenter. This concept is shown schematically on Figure 1.

The actual mass flow rate of the augmentation airflow is important to the functions of the test cell. Too little augmentation airflow: (1) allows the exhaust gas to recirculate back around to the engine inlet, resulting in hot spots and performance degradation; (2) allows the test cell to heat up; and (3) also results in an excess density of visible emittants, possibly violating Ringelmann number restrictions. Too much air entrainment induces excessive pressure gradients along and across the test cell augmenter, creating structural problems. Too much augmentation airflow can also cause errors in engine thrust measurements (Ref 1).

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*No distinction will be made between hush houses, where the engine remains mounted on the aircraft, and test cells, where the engine is tested off the aircraft.

Scope

For several reasons, very little thought has been given to test cell energy recovery.* First, jet engines are rarely tested for long durations. A few hours per day of test cell usage is maximum. Second, the dilution of the jet exhaust with the augmentation air decreases temperature gradients and, therefore, the potential for heat transfer from the exhaust. Even a 25% energy conversion efficiency is unlikely with most test cells. Finally, there are side effects to energy recovery that affect the ability of a test cell to perform its functions.

Waterwalls will decrease jet exhaust temperatures, beginning exactly at the nozzle. The environmental ramifications are, generally, bad. If combustion was complete, lower gas temperatures would decrease equilibrium concentrations of both NO_x and CO. At the higher power settings, however, combustion continues out into the augmenter. (Afterburning jets exhaust as much as 10% of their fuel (Ref 1).) Premature cooling of the exhaust will slow any combustion reactions still taking place. Unburned hydrocarbons, carbon monoxide, even raw fuel, could be carried into the atmosphere. The effect on particulates is uncertain; it can be presumed that changing the combustion chemistry will change the particulate concentration.

Lowering gas temperatures also changes the flow characteristics of the jet, changing kinetic energy, noise generation, and augmenter pressure gradients.

Some side effects of augmenter energy recovery are beneficial. Waterwalls will eliminate burnout problems of the liners and acoustic pads. Waterwalls will also decrease structural thermal shock by damping out temperature fluctuations at startup, shutdown, and while changing power settings.

Convection, water tube heat exchangers located close to the nozzle will introduce the same problems as waterwalls. In addition, the pressure gradient across the device could induce engine back pressure problems. Convection heat exchangers located further down the augmenter tube will have little effect on augmenter gas temperatures, but high engine back pressures still have to be faced.

Regardless, such a large energy source should be investigated. This report summarizes the first step: an analytical study of the economics of test cell energy recovery. The study is limited to thermal energy recovery; other forms of energy, such as kinetic energy, are not included. Side effects are also neglected. The analyses of the side effects will be lengthy; if test cell energy recovery is not economically feasible, an examination of side effects is moot.

Both steam and electricity are considered as products of energy recovery--steam directly and electricity off a Rankine cycle. Four possible heat exchanger** configurations are analyzed (see Figure 1):

*FFV, the Swedish aerospace company, has done some work in this area, including the construction of a small energy recovery system.

**The terms "heat exchanger" and "boiler" will be used interchangeably.

1. Convection, water tube heat exchanger located in the exhaust path at the augmenter exit

2. Waterwalls located near the augmenter inlet where the primary mode of heat transfer would be radiation

3. Waterwalls located near the augmenter exit (for this configuration, the primary mode of heat transfer would probably be convection)

4. Convection, water tube heat exchanger located near the nozzle of the engine

The plan-of-attack is to select several test cells in the San Diego area, evaluate their energy recovery potential, and then generalize the results, reinforced with parametric studies.

TEST CELL SIMULATION

The major burden is determining how much heat can be transferred from the jet exhaust to waterwalls or to a water tube heat exchanger. Once determined, steam generation and, subsequently, the economics of energy recovery can easily be computed. Sizes, shapes, wall constructions, and flow rates of test cells are almost limitless. The obvious approach to the analyses is to formulate and utilize a flexible mathematical model.

The complexities in modelling test cells are manifest. Re-examine Figure 1 and consider the following augmenter characteristics: multiple, nonconcentric flows, each at a different velocity; turbulence; flow separation; all three modes of heat transfer, simultaneously; extreme changes in temperatures and, thus, variable properties; and nonsymmetric, three dimensional geometries. In addition, some tests are of short duration, resulting in a highly transient situation. These complexities lead to a transient nonlinear problem with coupled energy, mass, and momentum transfer. Numerical techniques are necessary.

Even so, to make a test cell simulation attainable, assumptions must be made. The first assumption is to restrict the analyses to the augmenter duct. Jet and augmentation flows are treated as boundary conditions. For this present work, the emphasis is on heat transfer. The modelling tactics will be to describe fluid flow empirically but use first principles to determine heat transfer rates. With this in mind, the following additional assumptions are made:

1. Flows are one-dimensional, passing through a cylindrical augmenter

2. Steady state, steady flow is stipulated

3. Both the jet and augmentation air are ideal gases

4. Flow within the jet and within the augmentation air can be considered turbulent and perfectly mixed

5. Pressure gradients along the augmenter are negligible compared with temperature gradients and can be neglected

6. The jet nozzle is located exactly at the inlet to the augmenter tube

7. The augmenter walls are black, the jet is gray, and the augmentation air is transparent to thermal radiation

8. Axial radiation along the jet has a negligible effect on temperatures; all radiation is from jet to wall or from wall to wall

9. Heat transfer between the jet and the augmentation air is negligible compared with enthalpy changes due to mixing

10. Radiation from the jet to any heat exchanger located past the augmenter exit is negligble

Jet flow through the augmenter is empirically modelled using the curve fits of Becker et al. (Ref 2). Their data are from cold jets, and their test rig is smaller than test cells, necessitating some modification to the empirical constants. Specifically, Becker's relationships have been adjusted to be able to predict the arrival of the jet to the wall at locations observed experimentally at the hush houses, NAS Miramar (Ref 3 and 4).

To model the heat transfer, the augmenter tube is divided into axial segments, with the jet, augmentation flow, and inner and outer liners considered as separate sections. Temperature is assumed constant throughout each section-segment. Flows are perfectly mixed. Conservation of energy is then applied to each segment of each section, and the resulting equations, along with the equations of continuity, are solved simultaneously to determine temperatures and heat fluxes along the augmenter assembly. Due to the nonlinearities, an iterative technique is necessary; the Gauss-Seidel method, with relaxation, is employed for this purpose.

A detailed derivation of the model, including a discussion of the assumptions and the accuracy of the simulation, is enclosed as Appendix A.

ENERGY RECOVERY ECONOMICS

By supposition, a waterwall or a convection, water tube heat exchanger is added to the augmenter. Once potential test cell steam (or electricity) generation has been determined, its accumulated value is computed and compared with the initial cost of the waterwalls or water tube boiler, i.e., a savings-to-investment ratio (SIR) is calculated.

Appendix B includes a description of the relationships used to calculate SIR.

SAN DIEGO TEST CELL ENERGY RECOVERY

Five test cells located in the San Diego area are examined to determine their potential for energy recovery. These cells are selected to provide a variety of sizes and applications, ranging from a hush house down to a 2-foot-diam cell used for testing helicopter engines. Specifications and operating characteristics are summarized in Appendix C.

For these sites, energy is recovered in the form of 350°F saturated steam.* The energy recovery potential of each cell is illustrated by means of two figures. First, the accumulated present value of the generated steam is plotted against the economic life of the steam generation equipment. A Navy average is used for the value of the steam. Predictions of discount and escalation rates are employed (Ref 5). The second approach is to estimate the cost of the energy recovery equipment and plot the energy recovery potential as an SIR (again against the economic life of the equipment).

Hush House No. 1, NAS Miramar

Figures 2 and 3 show the potential for energy recovery in the NAS Miramar Hush House No. 1. The augmenter is large and approximately elliptical, with an overall length of 90 feet and a cross-section minor axis of about 11 feet. A water tube boiler at the augmenter exit (Configuration No. 1 of Figure 1) and both waterwall configurations are examined. These figures reflect testing of both the TF30 (F-14A) and J79 (F-4) at intermediate or afterburning. Although other engines are tested, the TF30 and J79, together, account for about 75% of the total hush house usage.

To summarize: the generation of steam in this facility is not economically feasible. Waterwalls produce very little steam and, in addition, generate this small amount very uneconomically. A large water tube heat exchanger, such as the 220,000 ft^2 device studied here, can generate plenty of steam during afterburning (A/B), as much as 95,000 lb/hr, but A/B testing is limited, and these large boilers are very expensive. This particular heat exchanger's estimated cost is about $6 million; thus, the SIR is low.

"A" Test Cell, NAS Miramar

The NAS Miramar "A" test cell, with an augmenter cross-sectional diameter of about 6 feet, can be classified as a "mid-sized" facility.

The economics of thermal energy recovery from this test cell is summarized on Figures 4 and 5. Waterwalls located near the augmenter inlet are not economically feasible. Waterwalls placed along the last 20 feet of the augmenter, however, are feasible although the steam generation is low (see Figure 4). For this configuration, the SIR reaches one after about 22 years. Water tubes placed near the augmenter

*Steam generation at 350°F, 138 psia is assumed throughout this work.

exit are economically feasible, and the steam generation rate is high, averaging 480,000 lb/hr at A/B and about 40,000 lb/hr at intermediate power settings. The SIR reaches one after 7 years.

Steam loads at NAS Miramar average about 30,000 lb/hr. Therefore, 480,000 lb/hr is considerably more steam than the base can consume. Thermal energy is not easily stored; a customer for the excess steam is necessary. If not found, much of the steam generated during A/B testing would not be used, and the above water tube SIR is inflated.

The TF30 is the only engine tested, yet this cell has had a very high frequency of A/B testing - 62.6 total hours in 1982 - and this accounts for much of the positive energy recovery economics. The practicality of installing some type of energy recovery system depends, to a very large extent, on continuing this schedule into the fut e.

Test Cell 11, NARF North Island

Test Cell 11 is a small cell used to test the T58 helicop engine. The diameter of the augmenter is about 2-1/2 feet; its length '^ feet.

Figures 6 and 7 summarize the energy recovery capability (ıs cell. Again, the installation of waterwalls is not economically feasible. The use of water tubes placed at the exit to the augmenter is economically feasible, with the SIR reaching one after 10 years. Approximately 8,000 lb/hr of steam is generated in a 6,600 ft^2 water tube heat exchanger, only a dribble compared with the steam load at NAS North Island.

Test Cell 14, NARF North Island

Test Cell 14 is a mid-sized facility used, primarily, to test the J79 gas turbine engine. The specifications of this cell are similar to those of the NAS Miramar "A" test cell.

The economics of energy recovery from cell 14 are illustrated by Figures 8 and 9. This cell is used infrequently, and any form of energy recovery is economically unfeasible.

Test Cell 19, NARF North Island

Test Cell 19 is also a mid-sized cell used to test the J79. It has an augmenter cross-sectional diameter of about 8 feet with a length of almost 80 feet.

Figures 10 and 11 show the potential for energy recovery in Test Cell 19. Both waterwalls and water tubes are economically marginal (i.e., within possible error in estimating the cost of the equipment). The steam generation rate is moderate. A 115,000 ft^2 water tube boiler will generate an average of 20,000 lb/hr of steam during intermediate power tests and about 310,000 lb/hr during A/B.

A comparison with the NAS Miramar "A" test cell is informative. Although Test Cell 19 is used more frequently, 210* hr/yr compared with about 135 hr/yr for the Miramar test cell, much less energy recovery

*Intermediate and afterburning only. Idle and part power settings do not produce temperature gradients high enough for thermal energy recovery and are not considered.

potential exists. The J79 exhausts somewhat less than the TF30, but the major difference is the low A/B testing, only 18 hr/yr in Test Cell 19 compared with more than 62 hr/yr in the Miramar "A" test cell.

PARAMETRIC STUDY OF TEST CELL ENERGY RECOVERY

A perusal of the five cells just analyzed plus the others described in Appendix C suggests that the test cells can be segregated into three size categories for parametric examination: large, mid-sized, and small. The distinction is based upon augmenter diameter. Large test cells will be represented by NAS Miramar Hush House No. 1, mid-sized cells by the NAS Miramar "A" test cell, and small cells by NARF North Island Test Cell 11.

Again, both the accumulated present value of the steam and SIR will be used as measures of feasibility. Perhaps somewhat redundant, the value of the steam is an indication of steam generation magnitudes while SIR is an indication of economics. Both figures are included also for documentation purposes. They can be used to evaluate test cells not specifically covered.

Large Test Cells

It was not emphasized in the discussion of NAS Miramar Hush House No. 1, but energy can be recovered in the large test cells, by water-walls or by downstream water tubes, only during afterburning tests. All other engine power settings are nonproductive. This is illustrated by Figures 12 and 13, which isolate the energy recovery capabilities of the different power settings. Augmenter exit water tubes are employed in these figures. This is the most efficient energy recovery configuration for Hush House No. 1. Note that some of the hush houses are capable of simultaneously testing two engines.

Although the A/B steam generation rate is potentially high, perhaps 100,000 lb/hr while testing the TF30, the total hours of A/B testing is very low. A testing frequency of 180 hr/yr, or an average of 0.5 hr/day, was assumed for Figures 12 and 13. This schedule is characteristic of intermediate power tests in the San Diego cells, but afterburner tests are conducted less frequently and are of a much shorter duration. An A/B test frequency of 30-40 hr/yr is a better estimate, thus, a 25-year SIR of 0.1, rather than 0.5 (see Figure 13).

The absence of any potential for energy recovery during gas turbine intermediate power tests can be attributed to the high augmentation air flow rates inherent in the large test cells. Augmentation air flows are typically 1,200 to 1,500 lb/sec compared with 400 to 500 lb/sec through mid-sized cells. The engine exhaust is cooled down to about 200°F by the time it reaches the wall; it is even cooler when it reaches the augmenter exit. At this temperature, the exhaust cannot, of course, be used to generate 350°F steam.

Energy recovery will never be economically feasible in the large test cells unless a system capable of recovering energy during intermediate power testing is employed. Either of two methods can accomplish this:

1. Recover the energy from the gas turbine exhaust before it is mixed with the augmentation air and cooled

2. Transfer the energy from the 200°F exhaust/air mixture to some highly volatile working fluid and use this fluid to generate electricity

The first method requires placing the heat exchanger up near the nozzle of the engine, Configuration No. 4 of Figure 1. Figures 14 and 15 parametrically examine this configuration when employed on large test cells. Figure 14 shows the potential of a 500 ft^2 heat exchanger. Approximately 85 2-inch-diam water tubes stretch across the augmenter just behind the test engine, probably near the maximum number of tubes that could reasonably be placed there. Note that it takes an average of 4 hr/day of testing to make this heat exchanger feasible.

Figure 15 sets the daily test cell operation at 0.5 hr/day and illustrates the effect of increasing heat transfer area (i.e., increasing the number of water tubes). It takes about 4,000 ft^2 of surface area to be economically feasible.* This is equivalent to 700 tubes stretched across the augmenter. In addition to the design problems innate to this configuration, the pressure drop across 700 tubes would probably induce unacceptable engine back pressures. Configuration No. 4 is not workable.**

The second method of recovering energy, employing a working fluid with a low boiling point to generate electricity, is the topic of a subsequent section.

Mid-Sized Test Cells

The examination of the San Diego cells, particularly the NAS Miramar "A" test cell, showed that energy recovery in mid-sized test cells could be economically feasible with a favorable test schedule. Steam can be generated from the exhaust of gas turbines tested at intermediate power in mid-sized cells. Augmentation air flow rates are moderately low, and the exhaust temperature is still about 400°F to 450°F when it reaches the augmenter wall.

Both water tubes and downstream waterwalls can generate steam; but the upstream waterwalls (Configuration No. 2) are of no use. Radiation from jet to the upstream walls is maximum; however, convection heat transfer from these walls to the cold augmentation air is also maximum (see Figures A-4, A-5, and A-6). There is little net heat transferred.

Figures 16 through 19 parametrically show the potential for energy recovery from engines being tested at intermediate power in the mid-sized cells. A comparison of Figures 16 and 17 with Figures 18 and 19 discloses the superiority of the water tubes over the waterwalls. Figures 16

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*Probably more since the cost of the heat exchanger was not increased with heat transfer area.

**The mid-sized and small test cells already have the potential to generate steam at intermediate. For them, there is no need to consider such a radical configuration.

and 18 show the water tubes generate about 60 times more steam (actually, 40,000 lb/hr compared with only 700 lb/hr by the waterwalls). Figures 17 and 19 show the water tube configuration has an SIR about four times higher. The superiority of water tubes exists with all sizes of test cells and can be attributed to the smaller heat transfer surface area of the waterwalls.

Yet, for even the downstream water tube heat exchanger to be economically feasible for mid-sized test cell energy recovery, about 1 hr/day of intermediate testing is required. This frequency, 365 hr/yr, is about twice the usage averaged by the San Diego facilities. More than a trace of A/B testing is still required in order to make energy recovery feasible.

A huge amount of steam can be generated when gas turbines are tested at A/B power settings in a mid-sized cell. Figure 20 is analogous to Figure 17 except that the engines are being tested while afterburning rather than at intermediate. Examining these two figures together is enlightening. They show the combinations of intermediate and A/B testing that, roughly, make energy recovery feasible in mid-sized cells, for example, 0.5 hr/day (180 hr/yr) of intermediate power testing with an SIR of about 0.3 after 25 years combined with 0.05 hr/day (18 hr/yr) of A/B testing with an SIR of about 0.7.

Small Test Cells

Energy recovery in small test cells involves different limitations than energy recovery in the larger cells. There is little or no augmentation air; therefore, temperature gradients are higher. However, engines tested in these cells are much smaller; there is much less thermal energy available for steam generation. Also there is no afterburning. It follows that steam can usually be generated in these cells but not very much of it.

Figures 21 and 22 summarize the energy recovery potential of small test cells. Steam is being generated at a rate of about 8,000 lb/hr. The 25-year break-even SIR occurs when test cell usage reaches about 36 hr/yr. A steam generation rate of only 8,000 lb/hr for perhaps 1/2 hr/day would not contribute much toward satisfying the steam load on the base and, despite any favorable SIR, would not warrant the tribulations involved in maintaining the boiler.

Thermal energy recovery in small test cells might become more attractive if several of them could be combined. The steam generation rate would not improve, unless several cells could be scheduled for testing at the same time, but the steam output would be steadier, and the total steam contribution much higher (for example, cells 9, 10, 11, and 12 at NARF North Island are all within a space of 60 feet and could, conceivably, all be ducted to a single heat exchanger).

ENERGY RECOVERED AS ELECTRICITY

The energy recovery analyses presented to this point were conducted with steam as the product. Electricity could also have been produced. Local conditions might make one or the other more valuable at a particular site, but, by using Navy averages for the values of energy, supply

and demand can be expected to prevail. Similar results would be anticipated from similar analyses using either steam or electricity as the product of energy recovery.

Two situations have been encountered, however, in which the generation of electricity would seem to be preferable. The first occurs when trying to recover energy from a large cell testing a gas turbine at intermediate power. Engine exhaust temperatures, diluted by the high augmentation air flow, are too low to generate 350°F steam. Since energy recovery during intermediate power testing is essential if the concept is to be economically feasible, some other product must be found. It was suggested that the energy in the jet exhaust could be transferred to some highly volatile working fluid (at high pressures but low temperatures) and this fluid expanded through a turbine to generate electricity.

The second situation in which the generation of electricity would appear to be preferable occurs during A/B testing in mid-sized cells located on the smaller Navy bases. The problem is excess steam. If a large water tube boiler is employed, as much as 500,000 lb/hr of 350°F steam can be generated from the exhaust of a TF30 during afterburning tests. This is more steam than many facilities can consume. Yet, for energy recovery to be feasible in mid-sized cells, the energy of afterburning engines must be utilized. Either the steam must be stored or a customer found for the excess. Neither is practical. Thermal energy is not easily stored, and potential customers for the steam would probably not be interested in such an erratic, unpredictable source. The generation of electricity rather than steam may be a solution to the problem. Many utility companies will buy (or compensate for) electricity generated locally.

Thus, the feasibility of energy recovery in the form of electricity is examined for the large and mid-sized test cells. These analyses are conducted by again employing the numerical model. It is assumed that electricity will be generated off a Rankine cycle, with energy supplied from the jet exhaust through waterwalls or through a water tube heat exchanger. A hypothetical organic fluid is substituted for the steam*; otherwise, the analyses are identical to previous efforts. The heat transfer efficiency is inherent in the model. Efficiencies of the other Rankine cycle components are stipulated,

$$\eta_{pump} = 0.75$$

$$\eta_{turbine} = 0.85$$

$$\eta_{generator} = 0.90$$

and multiplied by the energy recovered from the exhaust to provide a magnitude for electricity generation.

*The organic fluid is assumed to vaporize at 120°F with a heat of vaporization of 145 Btu/lb.

Figures 23 and 24 show the potential for energy recovery, as electricity, from jet engines being tested at intermediate power in the large cells. An improvement over steam is shown as would be expected (energy recovery in the form of 350°F steam was negligible). The improvement is small, however. A 25-year break-even requires a 4 hr/day intermediate power test frequency, about eight times the average of the San Diego cells. Too much A/B testing is still necessary in order to make energy recovery economically feasible in the large cells.

The generation of electricity in mid-sized cells shows somewhat more promise. When testing at intermediate, there is little difference in the economics of energy recovery with electricity or with steam as the product. Figures 16 and 17 can be used to evaluate energy recovery within reasonable accuracy. With the working fluid assumed* for this study, the generation of electricity from the energy in the exhaust of afterburning engines is less favorable. Figures 25 and 26 show the potential for generating electricity in mid-sized cells testing engines at A/B. The SIR for electricity generation is roughly one-third the SIR calculated for an analogous system generating steam. Still, the energy recovered as electricity from afterburning engines is equivalent to the energy required to generate 160,000 lb/hr of steam. This is quite significant if all this energy can now be used.

Economic feasibility is determined by energy recovery during both intermediate and afterburning tests. An example was provided earlier to illustrate the feasibility of energy recovery as steam in mid-sized cells. It is informative to repeat this same example with electricity as the product. Generating steam, 0.5 hr/day of intermediate testing combined with 0.05 hr/day of afterburning tests yields an energy recovery SIR of one after 25 years. Generating electricity (from Figures 17 and 26), 0.5 hr/day of intermediate testing must be combined with 0.15 hr/day (54 hr/yr) of A/B testing to yield the same SIR.

The generation of electricity in the NAS Miramar "A" test cell, a cell with a high frequency of afterburning tests, would be expected to be feasible, and it is. This cell is used an average 0.2 hr/day (72.9 hr/yr) for intermediate power tests, yielding an SIR of 0.25 after 25 years; and used approximately 0.17 hr/day (62.6 hr/yr) for A/B tests, yielding an SIR of 0.85. Thus, the total savings-to-investment ratio reaches about 1.1 after 25 years.

CONCLUSIONS

Thermal energy recovery is not economically feasible in hush houses and large test cells. The augmentation air flow rates are very high, rapidly cooling the engine exhaust and eliminating temperature gradients necessary for steam generation. Electricity generation off an organic Rankine cycle, although economically better, still requires too much test cell usage to be feasible.

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*The selection of an optimum organic fluid is itself a major task, the choice varying with cell geometry, test schedule, and other conditions.

Energy recovery in most small test cells is unfeasible. These facilities are normally used for testing a single class of gas turbine; the hours of operation are limited. Even if the SIR is favorable, the engines are small and steam or electricity generation is so low that it would not be worth the effort. An exception might occur if energy recovery systems for several small cells could be combined (e.g., ducting the augmenter exit gases of several cells to a single heat exchanger).

Energy recovery in the mid-sized cells is marginal, with the feasibility depending upon cell usage and energy loads. Steam generation rates can be excellent because augmentation flows are lower than in the large cells, yet mid-sized cells are often used for testing the larger engines. If the Naval facility is small, steam generation rates may even exceed the steam demand, particularly when testing afterburning. When this occurs, the generation of electricity is an alternative to be considered.

A water tube boiler located outside the augmenter exit, Configuration No. 1 of Figure 1, is the only practical choice for an energy recovery heat exchanger. Augmenter waterwalls and water tubes inside the augmenter have too small a heat transfer surface area. The steam generation potential is much too low.

COMMENTS

Boiler design problems have not been examined, but they will tend to discourage thermal energy recovery. Boilers do not function particularly well when subjected to cyclic operation. Not only is the incessant mechanical expansion and contraction of the pressure components a difficult design problem, but the water swell occurring at each start up presents a control problem and certainly results in a significant quantity of boiler water wastage. Tube or waterwall chemical corrosion can be expected. Surface erosion is also probable. A gas velocity of 150 ft/sec is about the practical limit that the heat exchanger components could withstand. If the heat exchanger is outside the augmenter, the engine exhaust can be slowed to acceptable velocities before entering the device. For waterwalls and for water tubes inside the augmenter, heat transfer surface erosion would be a very serious problem. In addition, water tubes inside the augmenter would have to withstand blasts of 3,000°F exhaust whenever afterburning tests were conducted.

Although not intentionally included in these analyses, some knowledge of potential side effects was acquired as a byproduct of the heat transfer calculations. The only energy recovery configuration that has a significant effect on flow characteristics inside the augmenter is upstream water tubes (Configuration No. 4 of Figure 1). It is unlikely that this configuration will ever be employed; the design problems are presumably insurmountable. Very little energy is removed from the jet by waterwalls, and side effects will probably be negligible (compare stack gas temperatures on Table 1 with and without waterwalls). The downstream water tubes, Configuration No. 1, have an appreciable effect on flow characteristics, but only outside the augmenter tube.* Thus, side effects to test cell energy recovery may not be a major factor.

*The effect on engine back pressures could still be a problem.

Stack gas temperatures are another byproduct of the heat transfer calculations. Table 1 summarizes the effect of energy recovery boilers on the temperature of the jet exhaust. As suggested above, the effect of the waterwalls is very small. Convection, water tube configurations, however, significantly lower stack gas temperatures, a beneficial side effect when further environmental or acoustical treatments are necessary.

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NOMENCLATURE

A	Surface area
C_p	Specific heat
C_t	Craya-Curtet Number, Equation A-1
COST	Assumed value of steam, Equation B-1
D	Diameter
D_{EQV}	Equivalent diameter
DISC	Discount rate
e	Boiler effectiveness
ESC	Escalation rate of the cost of steam or electricity, Equation B-2
F, F1	Radiation shape factors
h	Enthalpy
$\hat{h}$	Convective heat transfer film coefficient
k	Coefficient of thermal conductivity
$\dot{M}$	Mass flow rate
$\Delta\dot{M}$	Augmentation flow entrained by the jet
PRICE	Initial cost of waterwalls or heat exchanger, Equation B-3
PV	Present value
$\dot{q}_{COND}$	Conduction heat transfer
$\dot{q}_{CONV}$	Convection heat transfer
$\dot{q}_{RAD}$	Radiation heat transfer
$\dot{q}_{STM}$	Heat transferred from jet and augmentation airflow to the steam
r*	Ratio of jet nozzle area to cross-sectional area of augmenter, Equation A-1
R	Radius
R(Z)	Radius at distance Z from the augmenter inlet

SIR	Savings-to-investment ratio, Equation B-3
T	Temperature
TIME	Average utilization of the test cell, Equation B-1
UA	Product of boiler overall heat transfer coefficient and heat transfer area
VALUE	Value of the steam or electrictiy generated
V	Velocity
Z	Distance from the augmenter inlet
α	Radiation absorptivity
Δh_{fg}	Heat of vaporization of steam
ΔT_m	Logarithmic mean temperature difference, Equation A-10
ε	Radiation emissivity
μ	Viscosity
ρ	Density
σ	Stefan-Boltzmann constant
η	Efficiency

Subscripts

AUG	Refers to augmenter tube
GAS	Refers to the mixed jet and augmentation flow
I, J	Segment node designations, see Figure A-1
IL	Refers to inner liner of augmenter
I→J	From segment "I" to segment "J", etc.
JET	Refers to jet exhaust
JET→IL	From the jet to the inner liner of augmenter, etc.
N	Number of axial segments of the augmenter tube, see Figure A-1
NN	Economic life of waterwalls or energy recovery heat exchanger, Equation B-2
OL	Refers to outer liner of augmenter

REF	Reference, used for defined properties
SEC	Refers to augmentation (secondary) air flow
STACK	Refers to jet and augmentation flow leaving the convection boiler
STM	Refers to steam generated
TUBE	Refers to water tubes of convection heat recovery heat exchanger
∞	Refers to ambient conditions

Abbreviations

A/B	Afterburning
INTER	Intermediate
ORC	Organic Rankine cycle

Table 1. Effect of Gas Turbine Test Cell Energy Recovery on Stack Gas Temperatures

Engine	Type of Energy Recovery Equipment	Total Gas Flow Out the Stack, Jet Exhaust and Cooling Flow (lb/sec)	Avg Stack Gas Temp Without Energy Recovery (°F)	Avg Stack Gas Temp With Energy Recovery (°F)
a. Large Test Cell				
J79 afterburning	(1) With water tubes at augmenter exit, 250,000 ft^2	1,700	420	370
	(2) With waterwalls along last 50 feet of augmenter	1,700	420	415
TF30 afterburning	(1) With water tubes at augmenter exit, 220,000 ft^2	1,450	650	425
	(2) With waterwalls along last 60 ft of augmenter	1,450	650	640
b. Mid-Sized Test Cell				
TF30 at intermediate	(1) Water tubes at augmenter exit, 80,000 ft^2	660	425	370
	(2) Waterwalls along last 20 ft of augmenter	660	425	420
TF30 afterburning	(1) Water tubes at augmenter exit, 80,000 ft^2	660	1,220	560
	(2) Waterwalls along last 20 ft of augmenter	660	1,220	1,205
c. Small Test Cell				
T58 at intermediate	(1) Water tubes at augmenter exit, 6,600 ft^2	20	820	465
	(2) Waterwalls along last 38 ft of augmenter	20	820	810

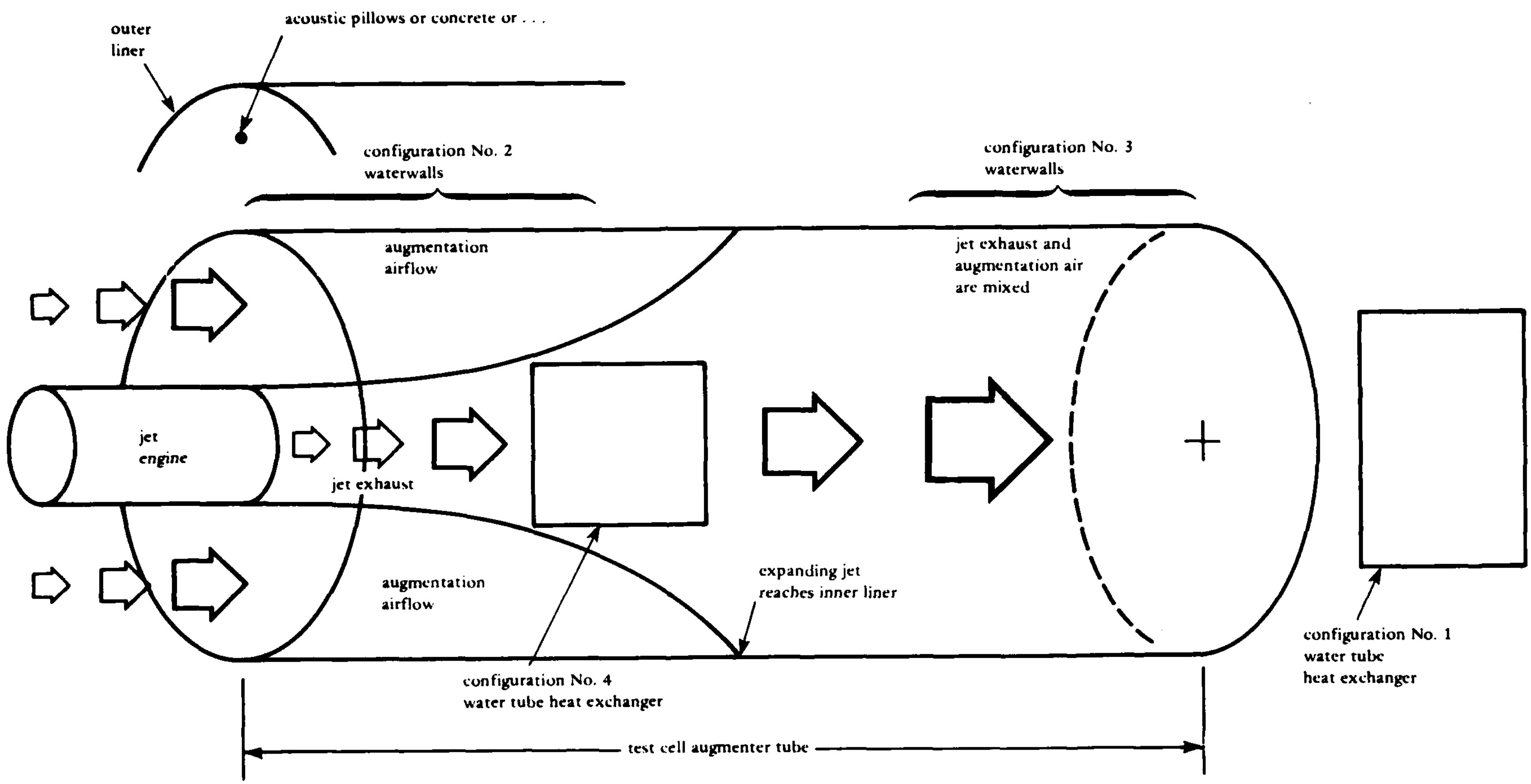

Figure 1. Schematic of gas turbine engine test facility augmenter tube and proposed boiler configurations.

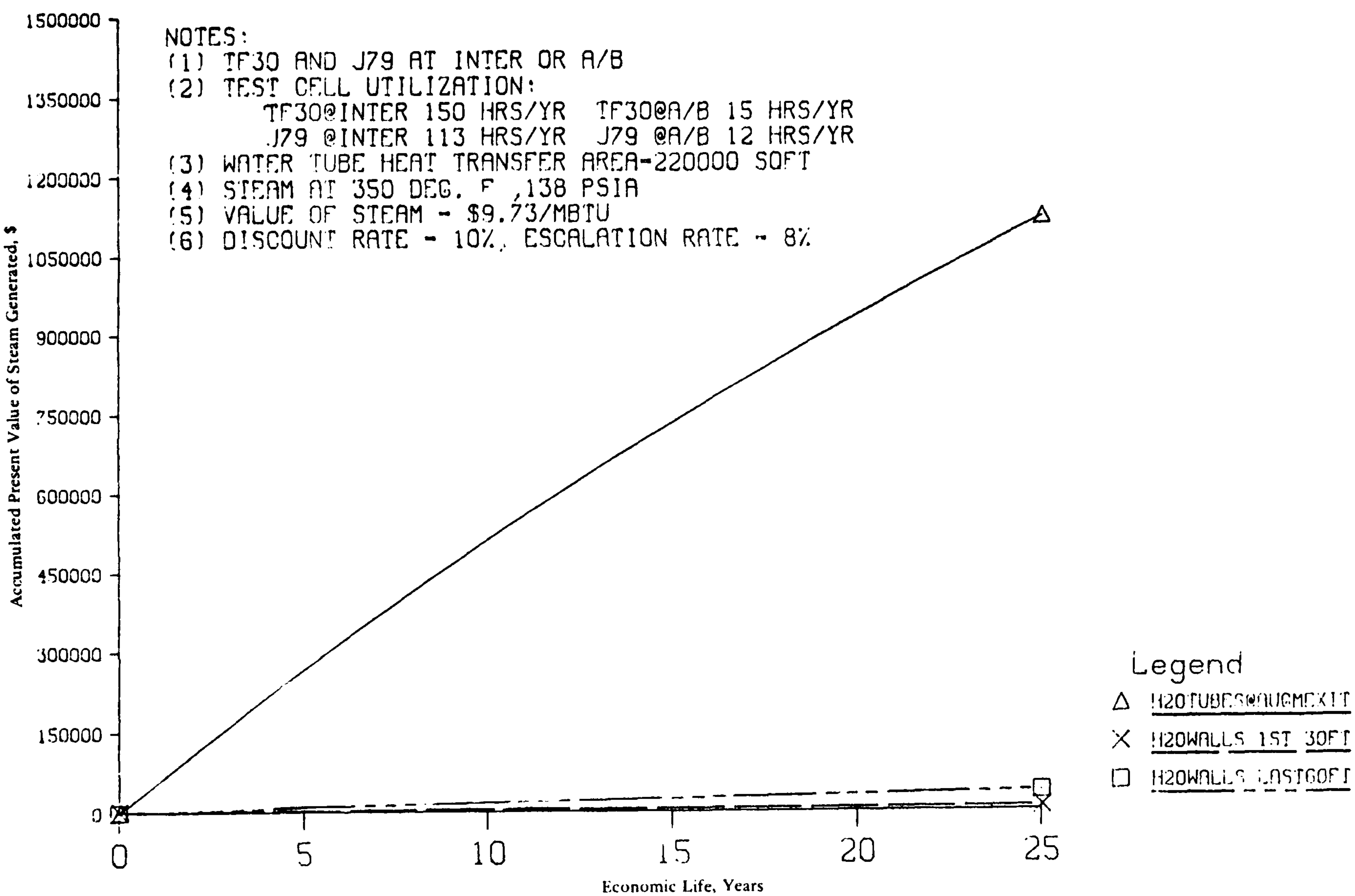

Figure 2. Generation of steam in gas turbine engine test facilities: NAS Miramar Hush House No. 1.

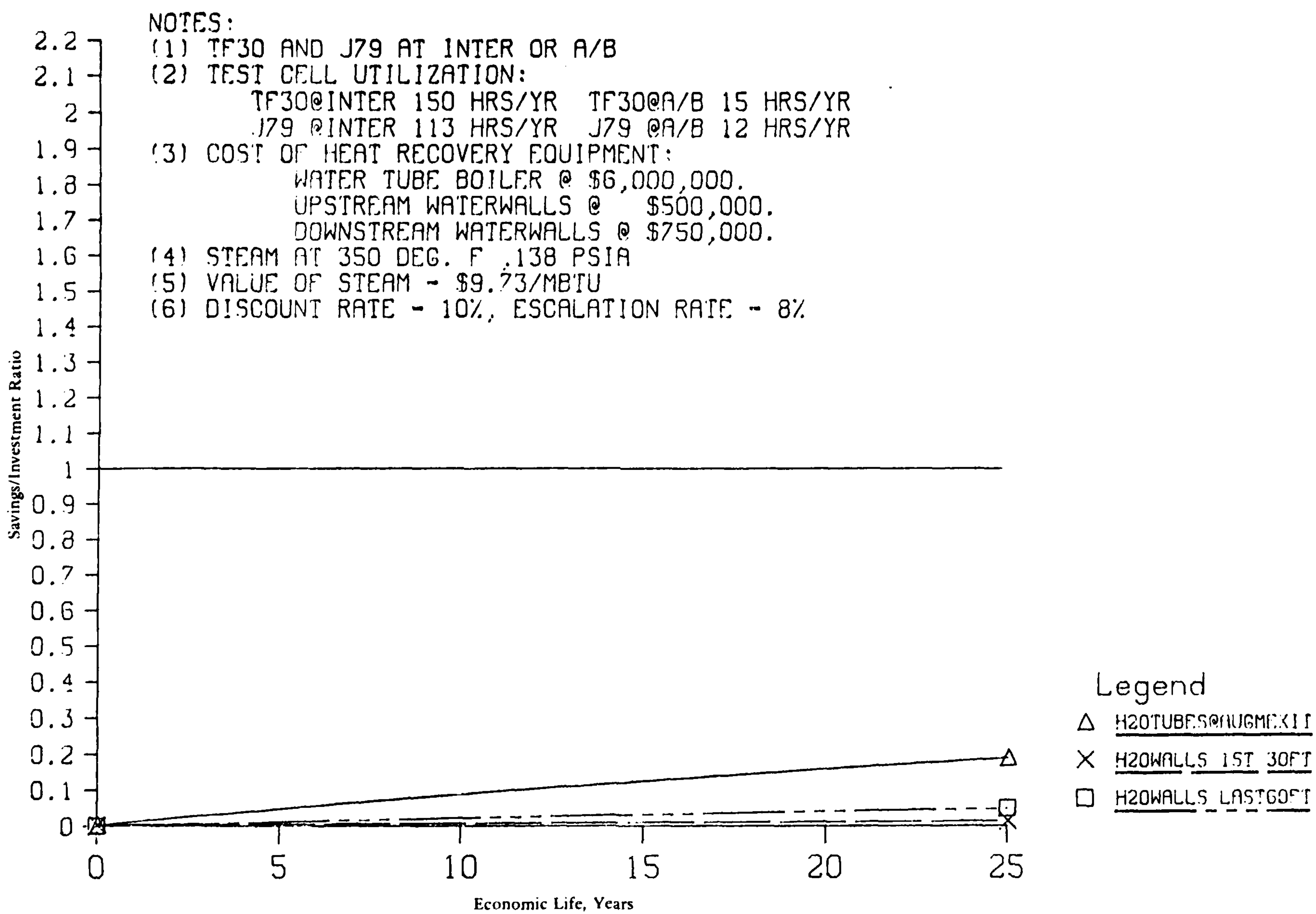

Figure 3. Economics of gas turbine engine test facility energy recovery: NAS Miramar Hush House No. 1.

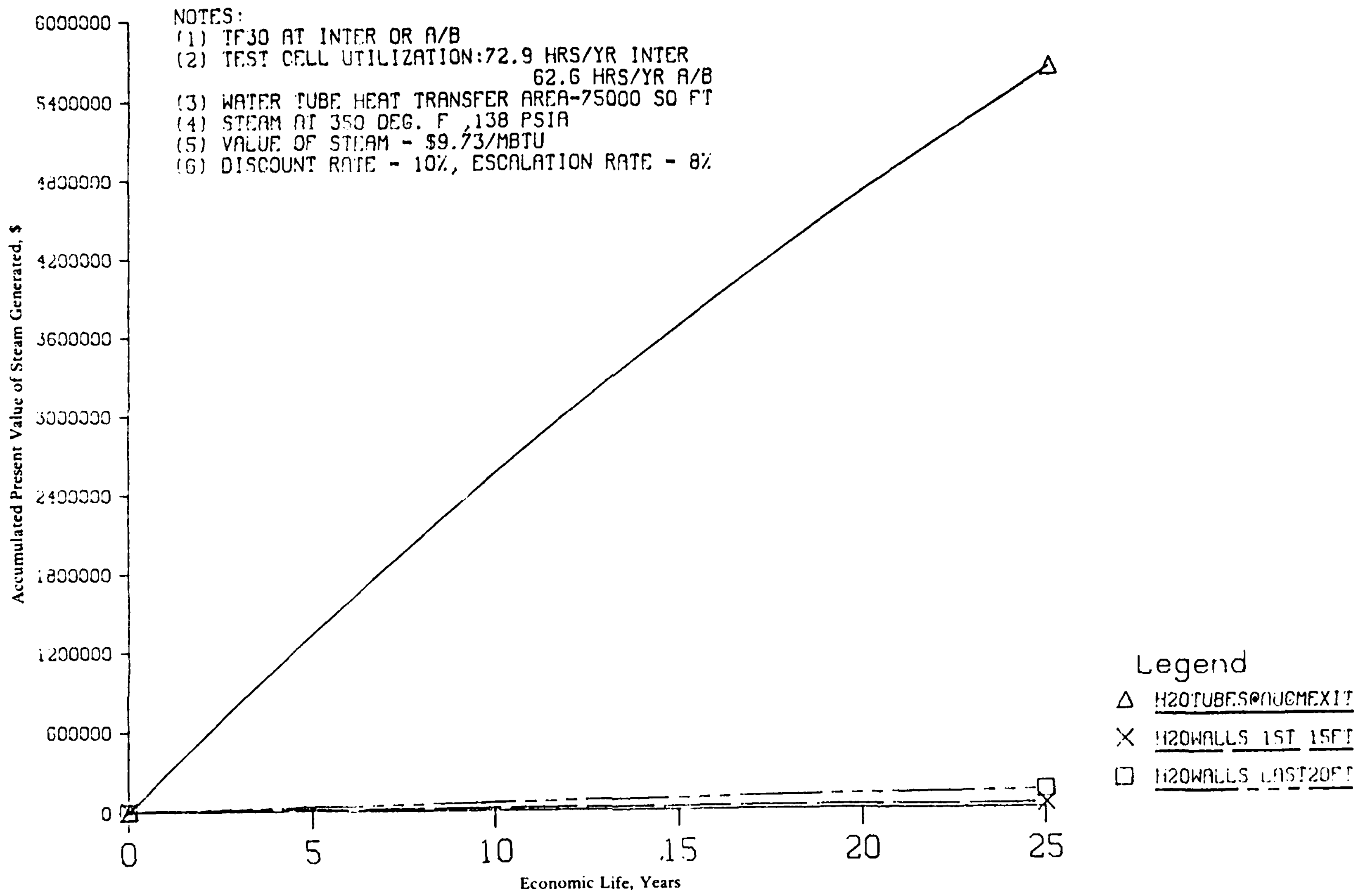

Figure 4. Generation of steam in gas turbine engine test facilities: NAS Miramar Test Cell "A".

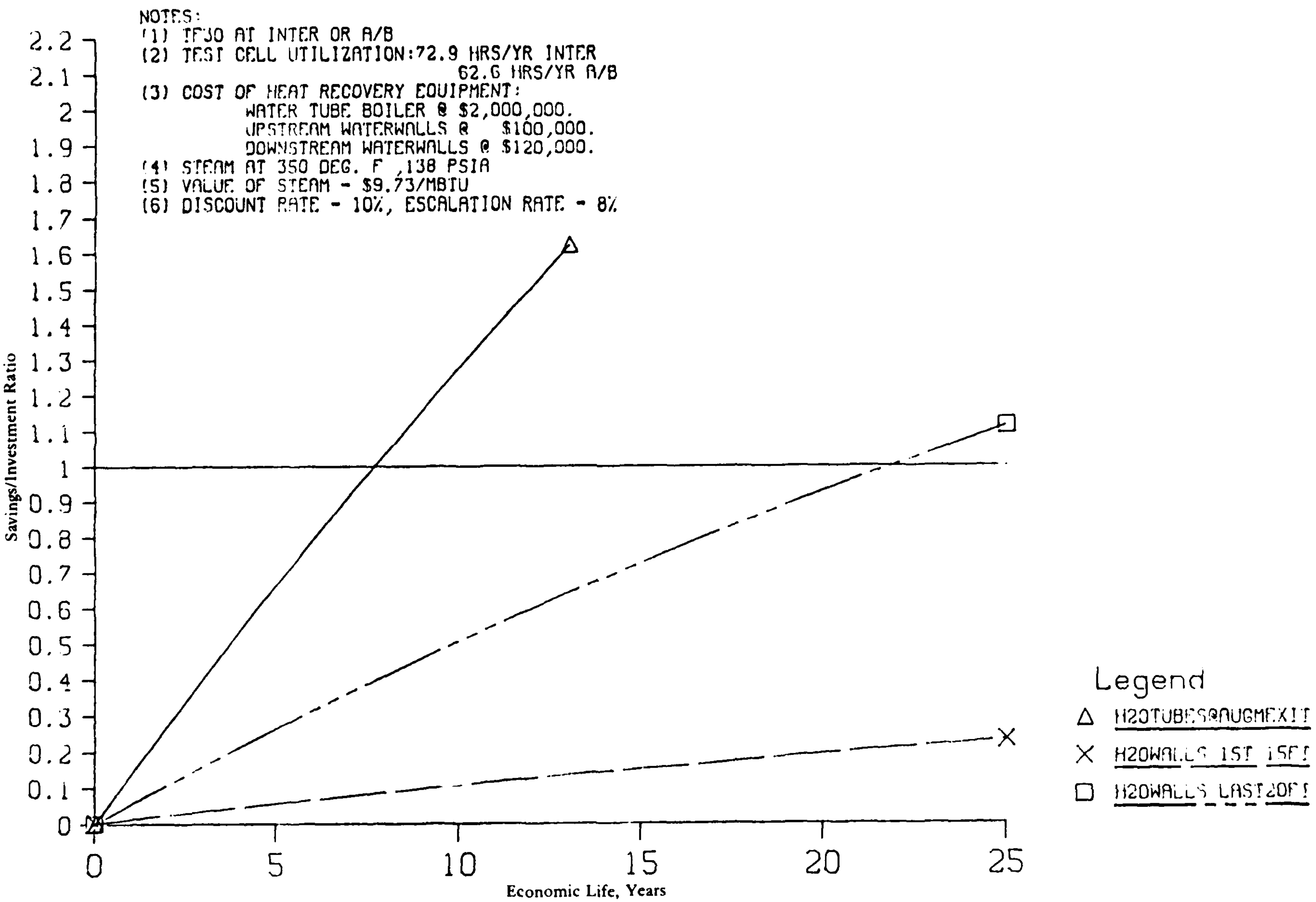

Figure 5. Economics of gas turbine engine test facility energy recovery: NAS Miramar Test Cell "A".

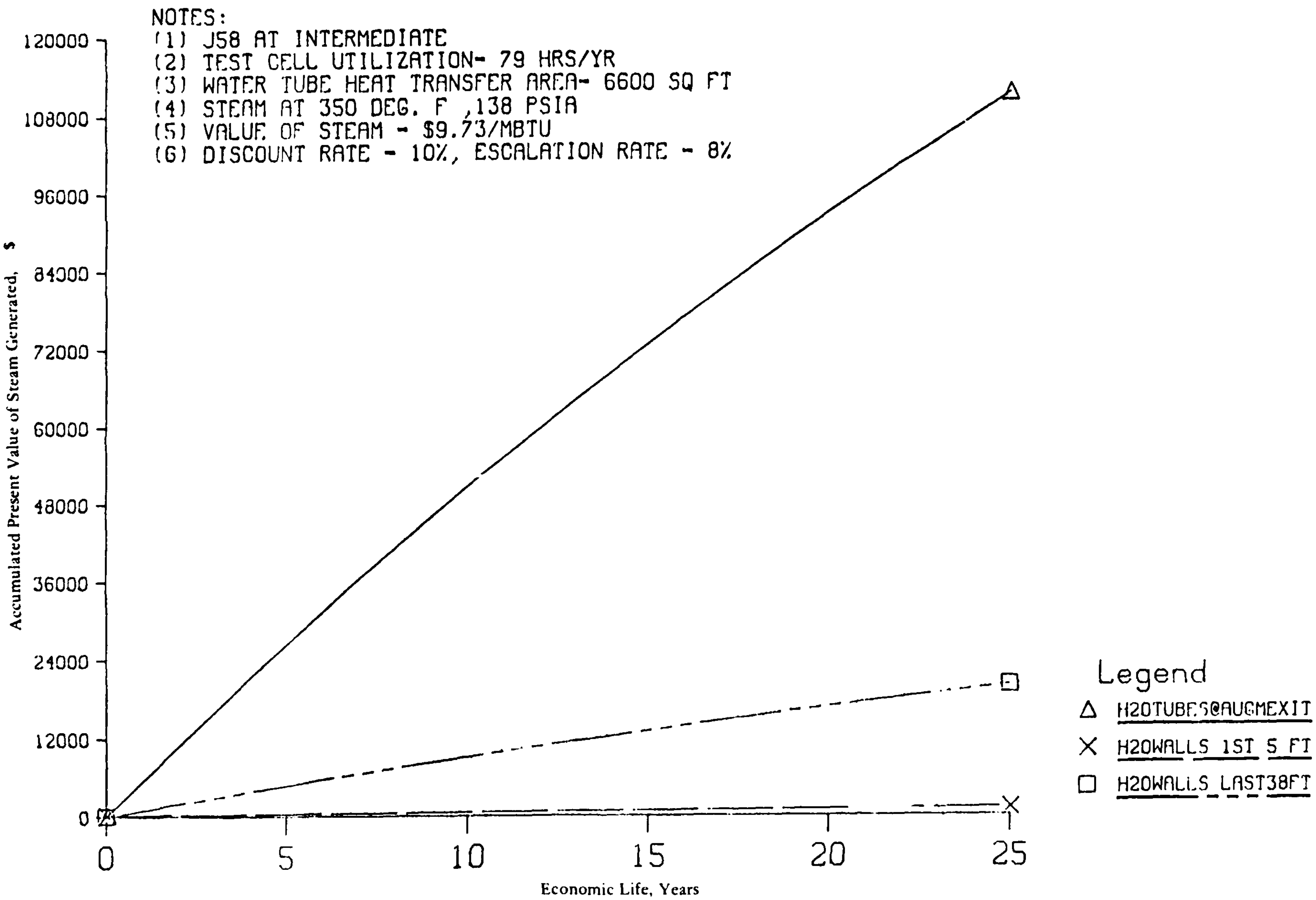

Figure 6. Generation of steam in gas turbine engine test facilities: NARF/NAS North Island Test Cell 11.

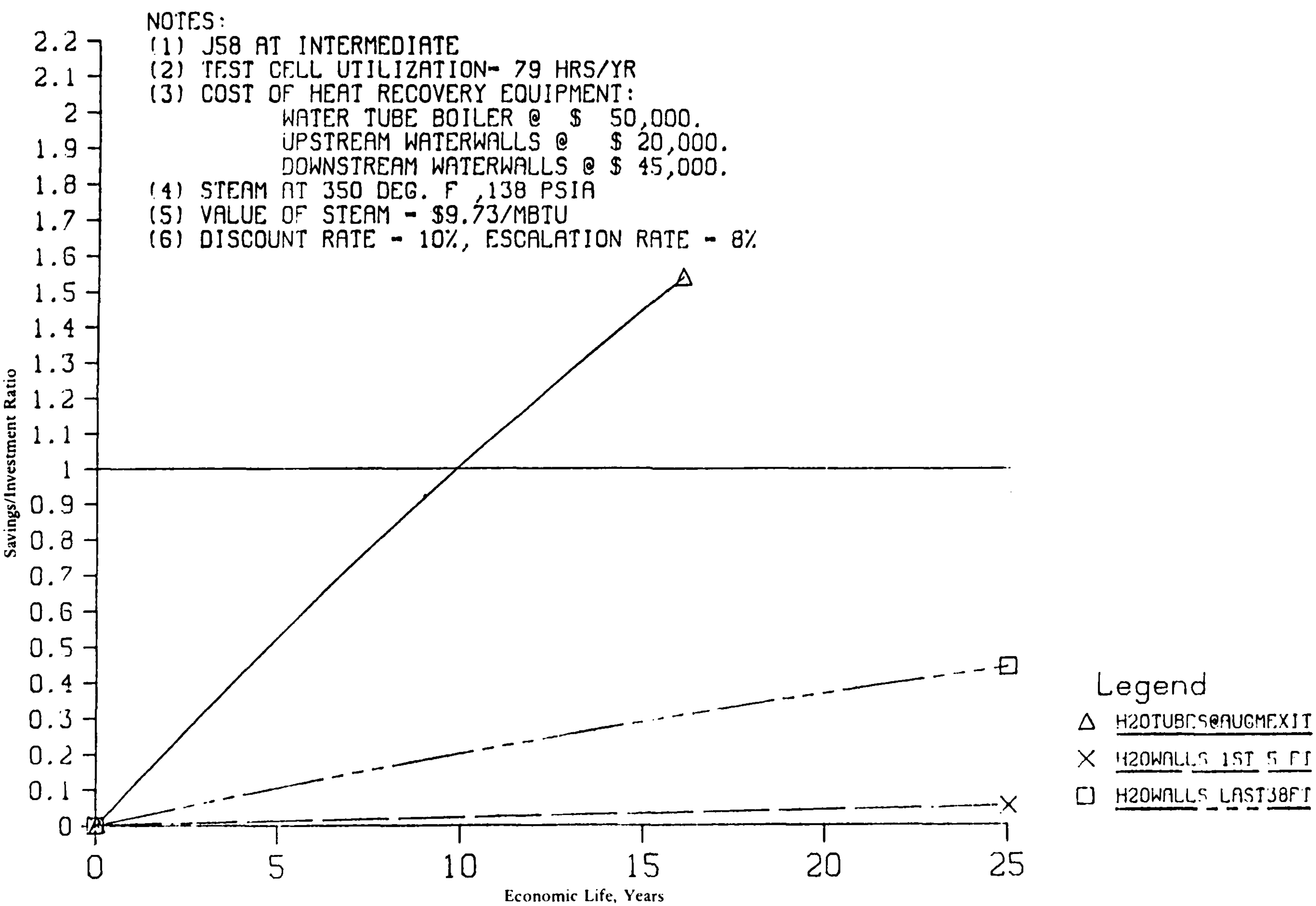

Figure 7. Economics of gas turbine engine test facility energy recovery: NARF/NAS North Island Test Cell 11.

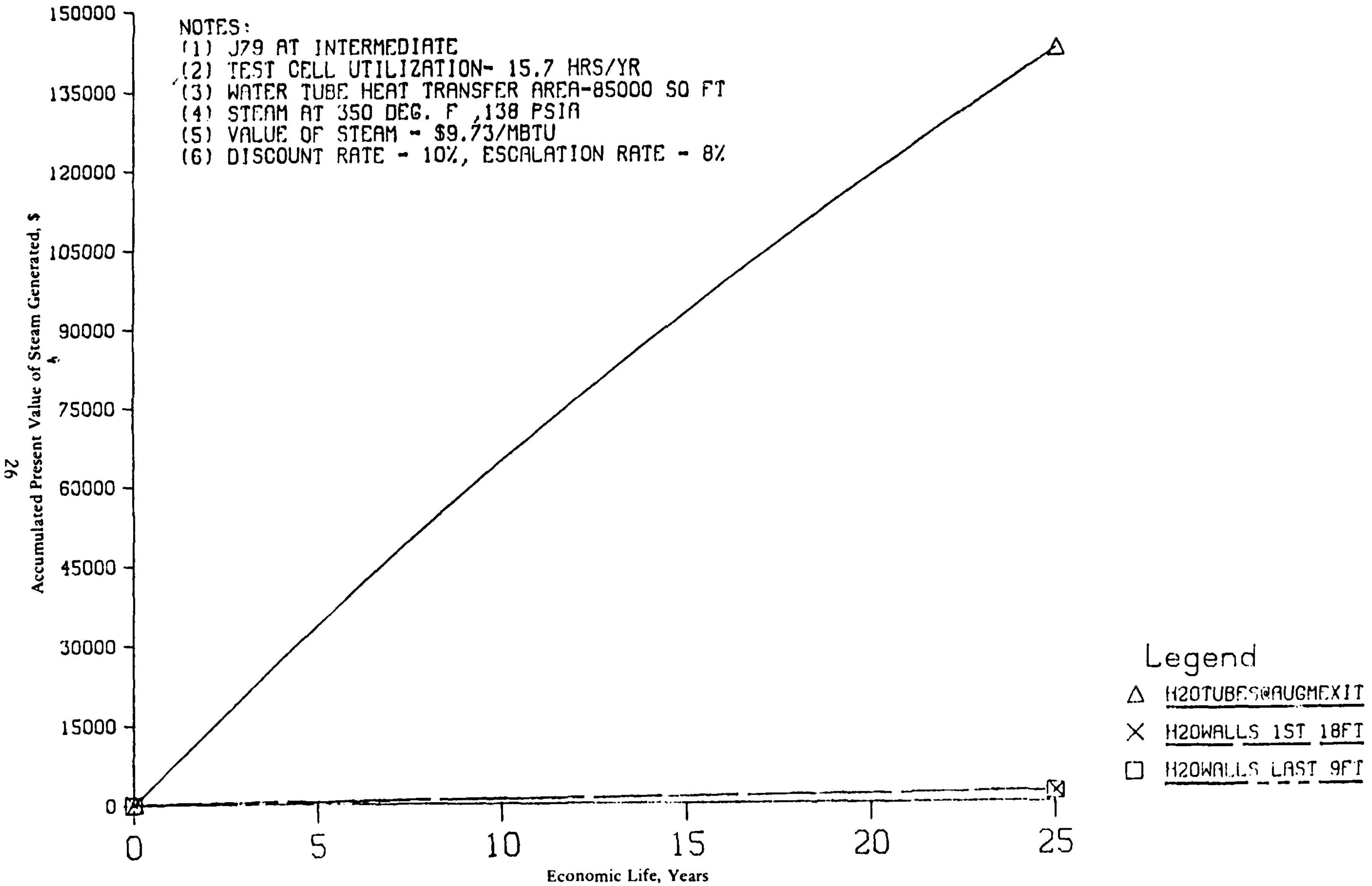

Figure 8. Generation of steam in gas turbine engine test facilities: NARF/NAS North Island Test Cell 14.

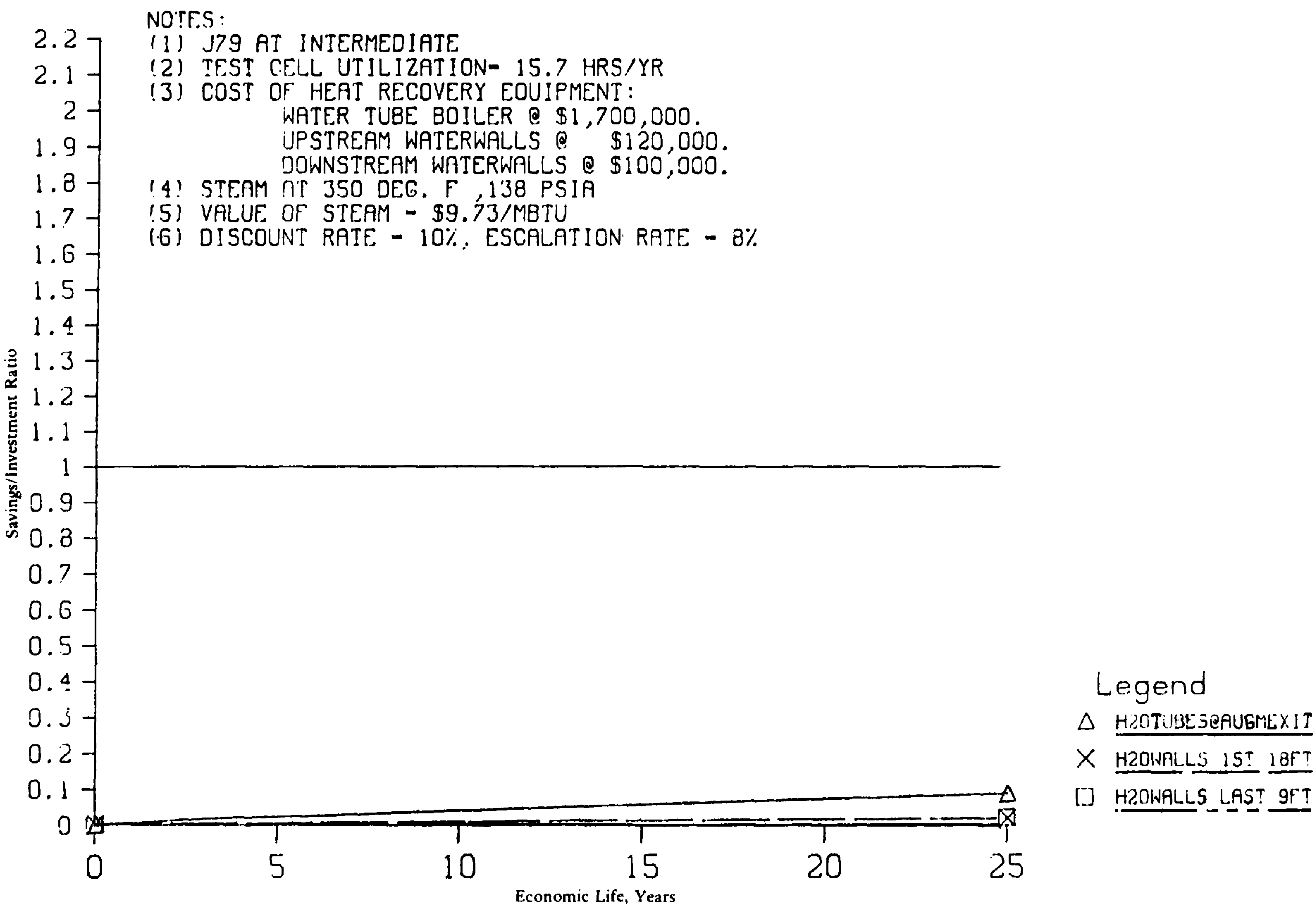

Figure 9. Economics of gas turbine engine test facility energy recovery: NARF/NAS North Island Test Cell 14.

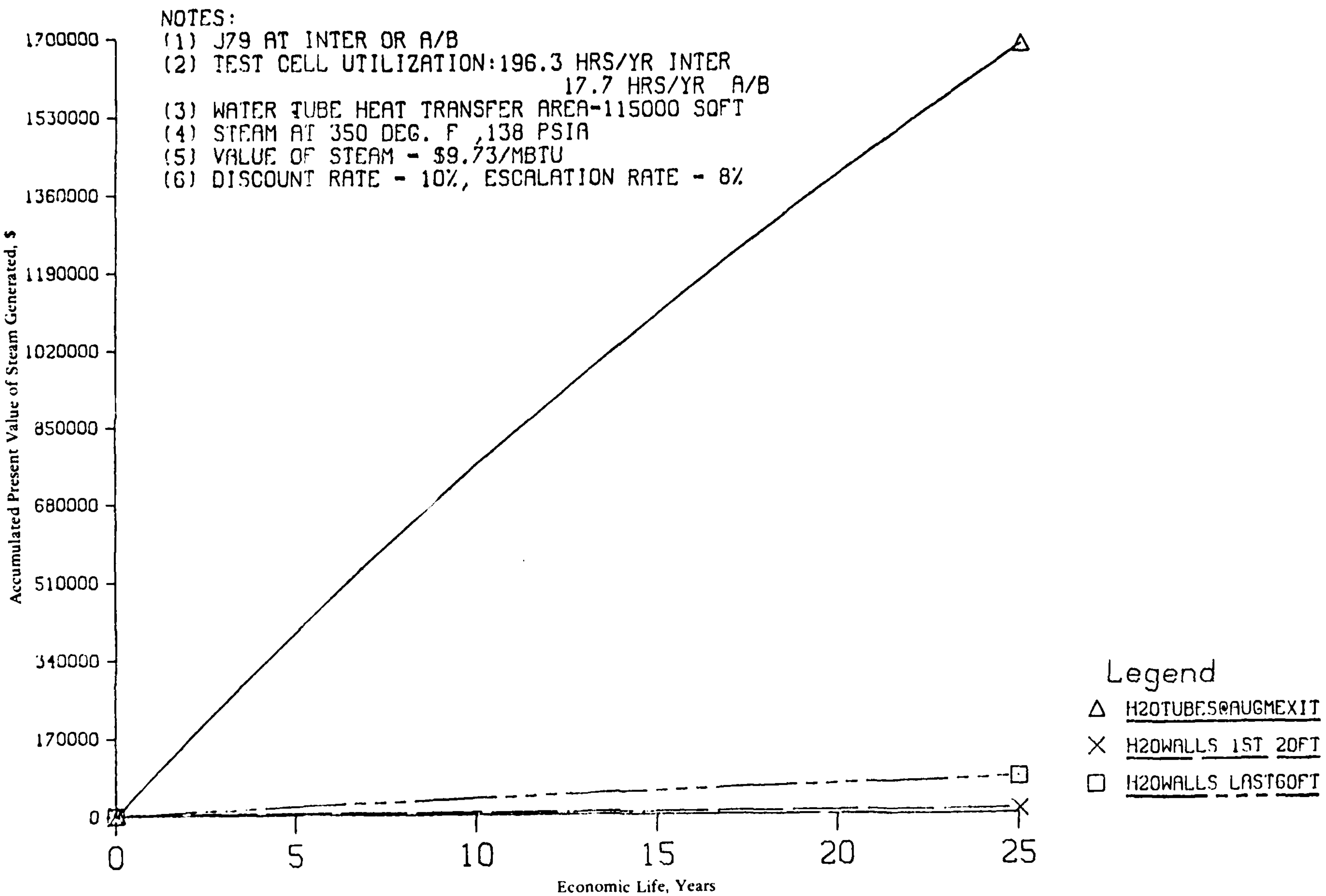

Figure 10. Generation of steam in gas turbine engine test facilities: NARF/NAS North Island Test Cell 19.

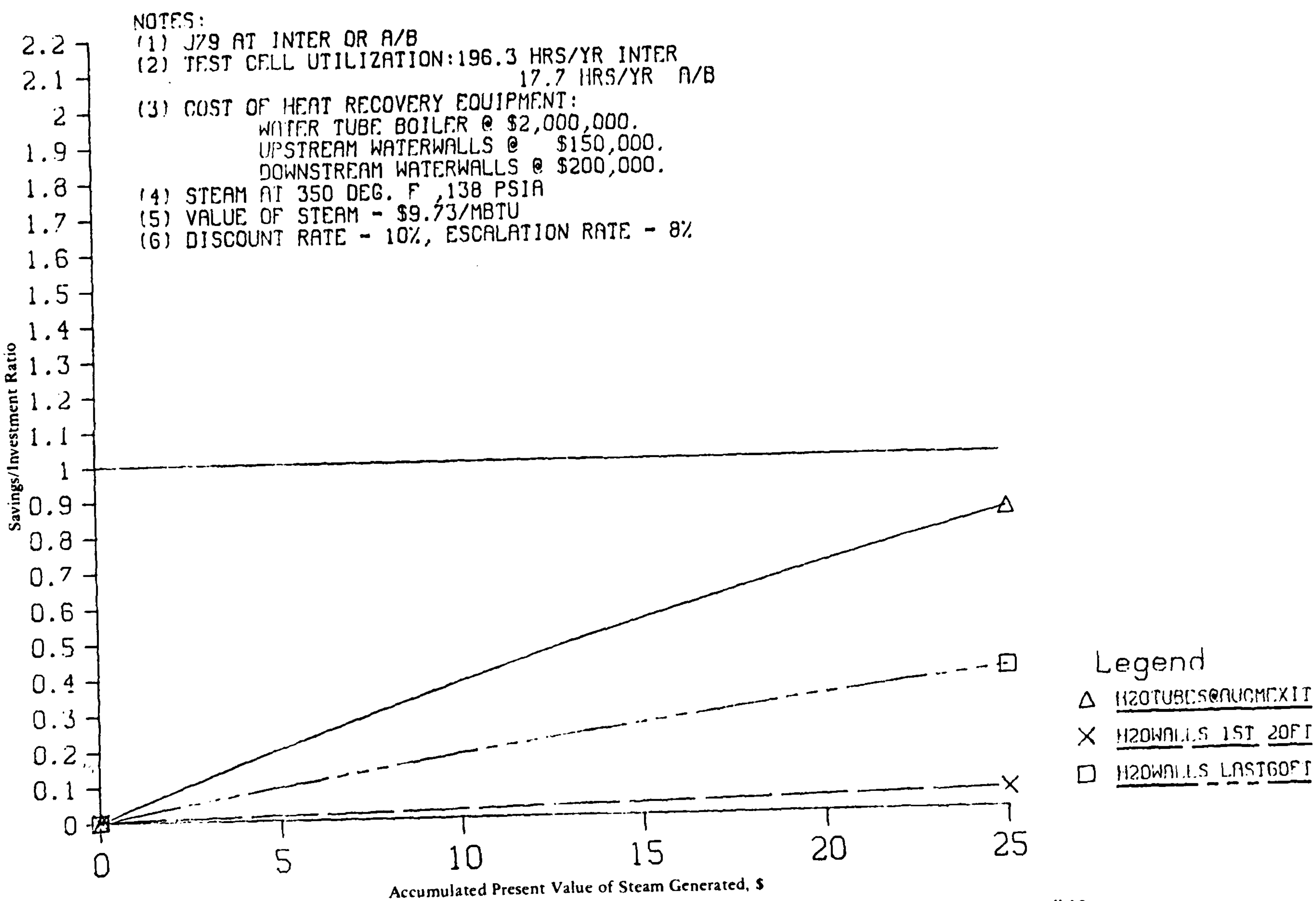

Figure 11. Economics of gas turbine engine test facility energy recovery: NARF/NAS North Island Test Cell 19.

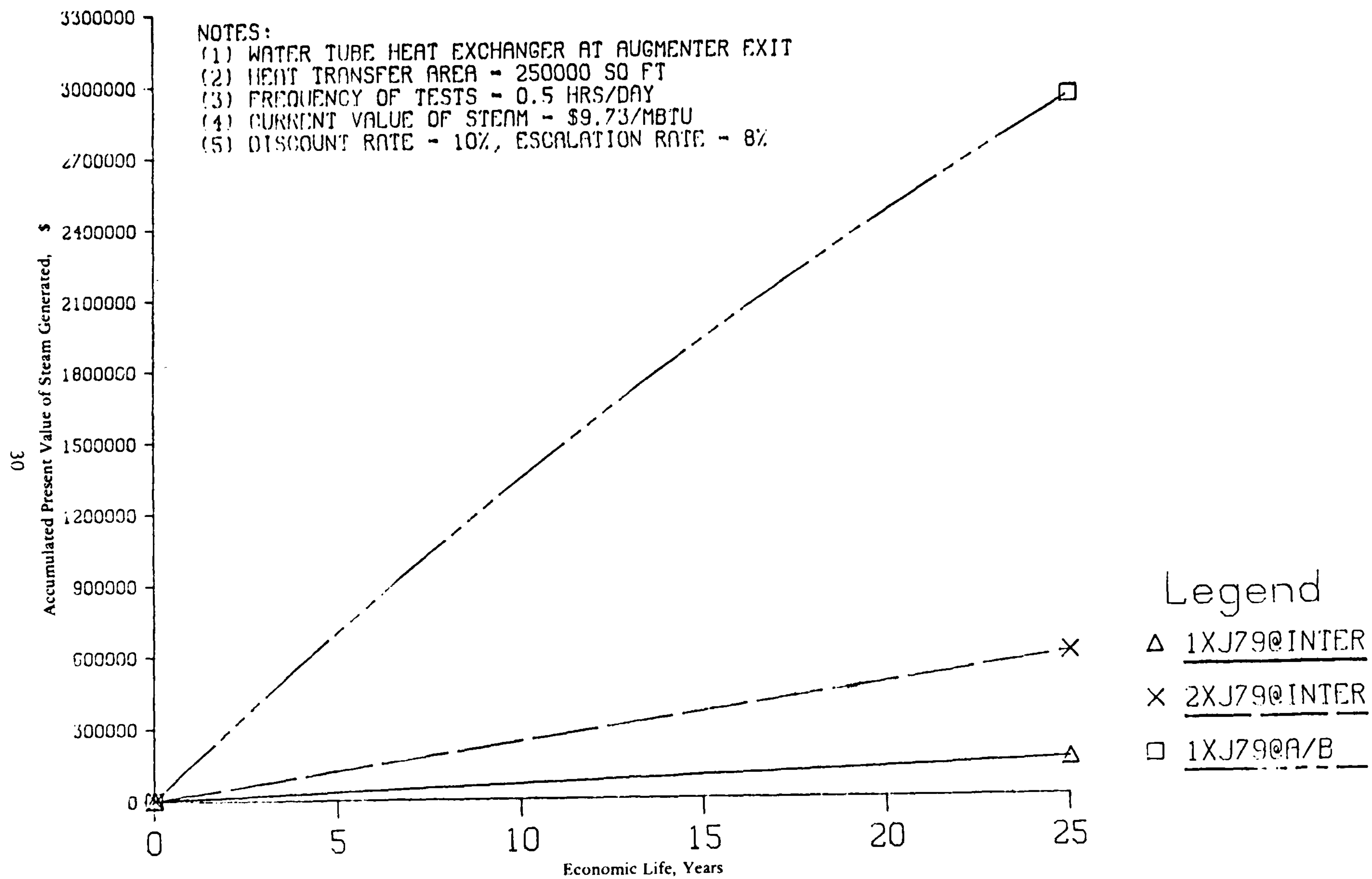

Figure 12. Effect of engine power setting on the generation of steam in a typical large gas turbine test cell.

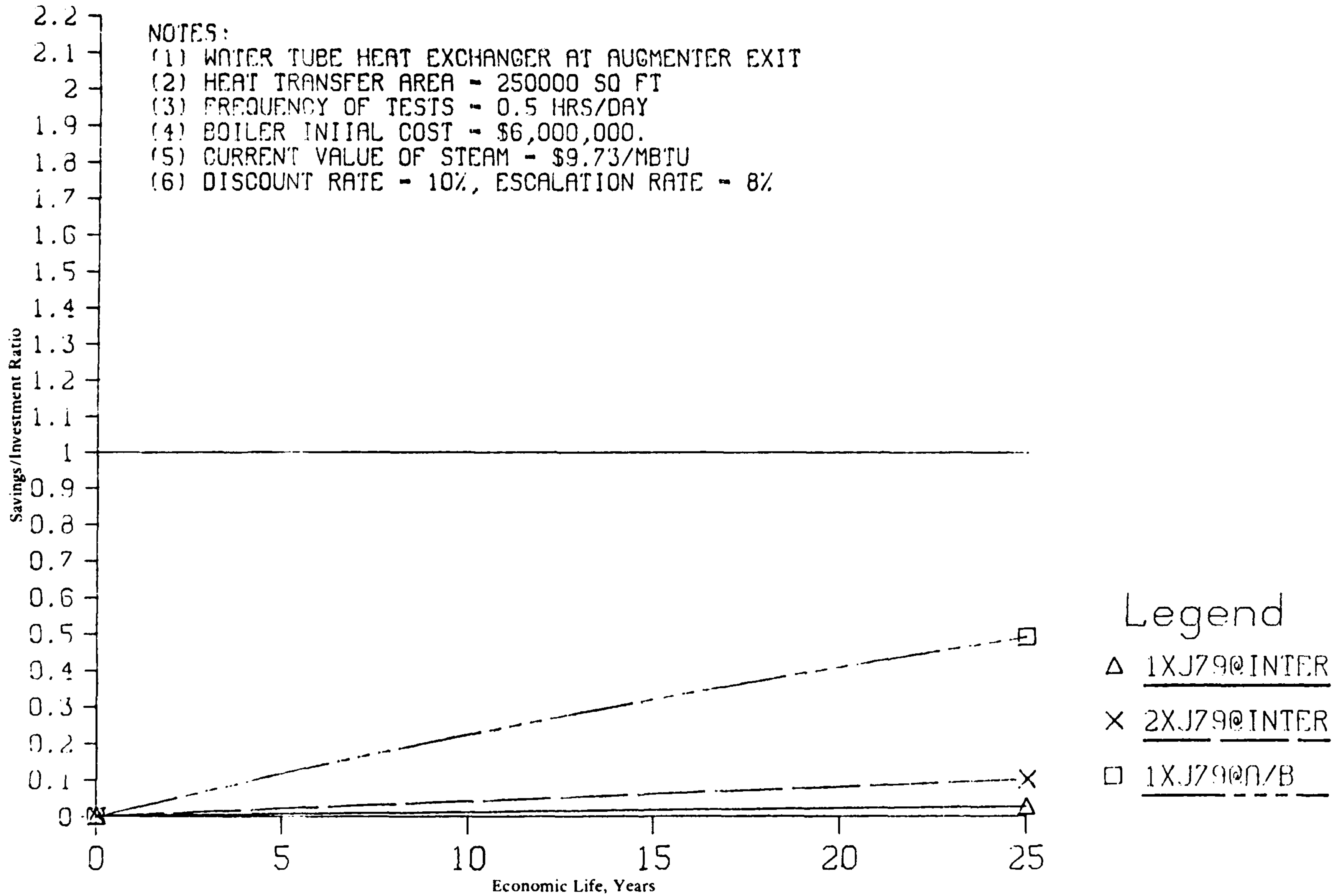

Figure 13. Effect of engine power setting on the economics of energy recovery in a typical large gas turbine test cell.

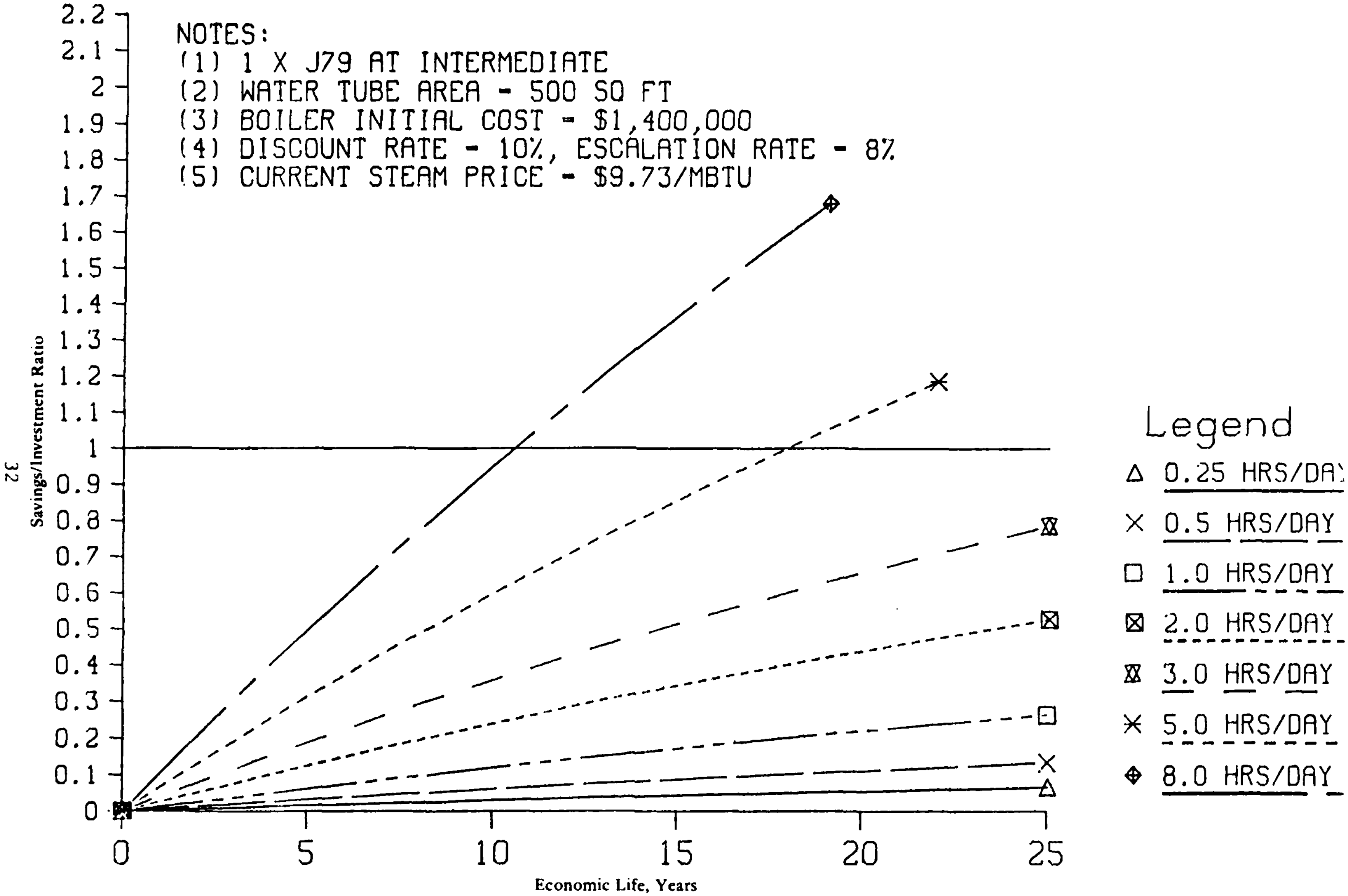

Figure 14. Economics of energy recovery from a typical large gas turbine test cell by using water tubes located near the nozzle.

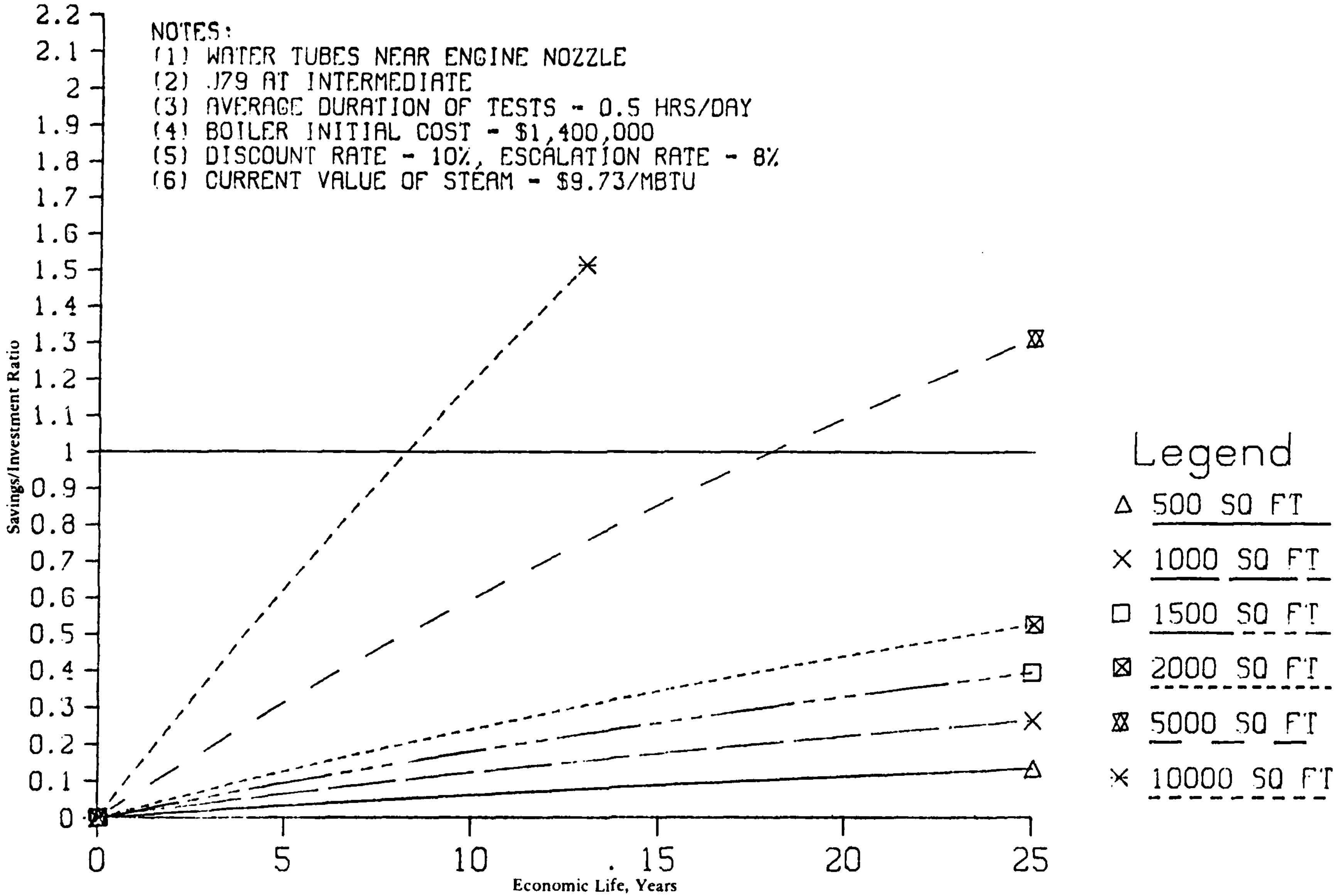

Figure 15. Effect of heat transfer area on energy recovery in a typical large test cell.

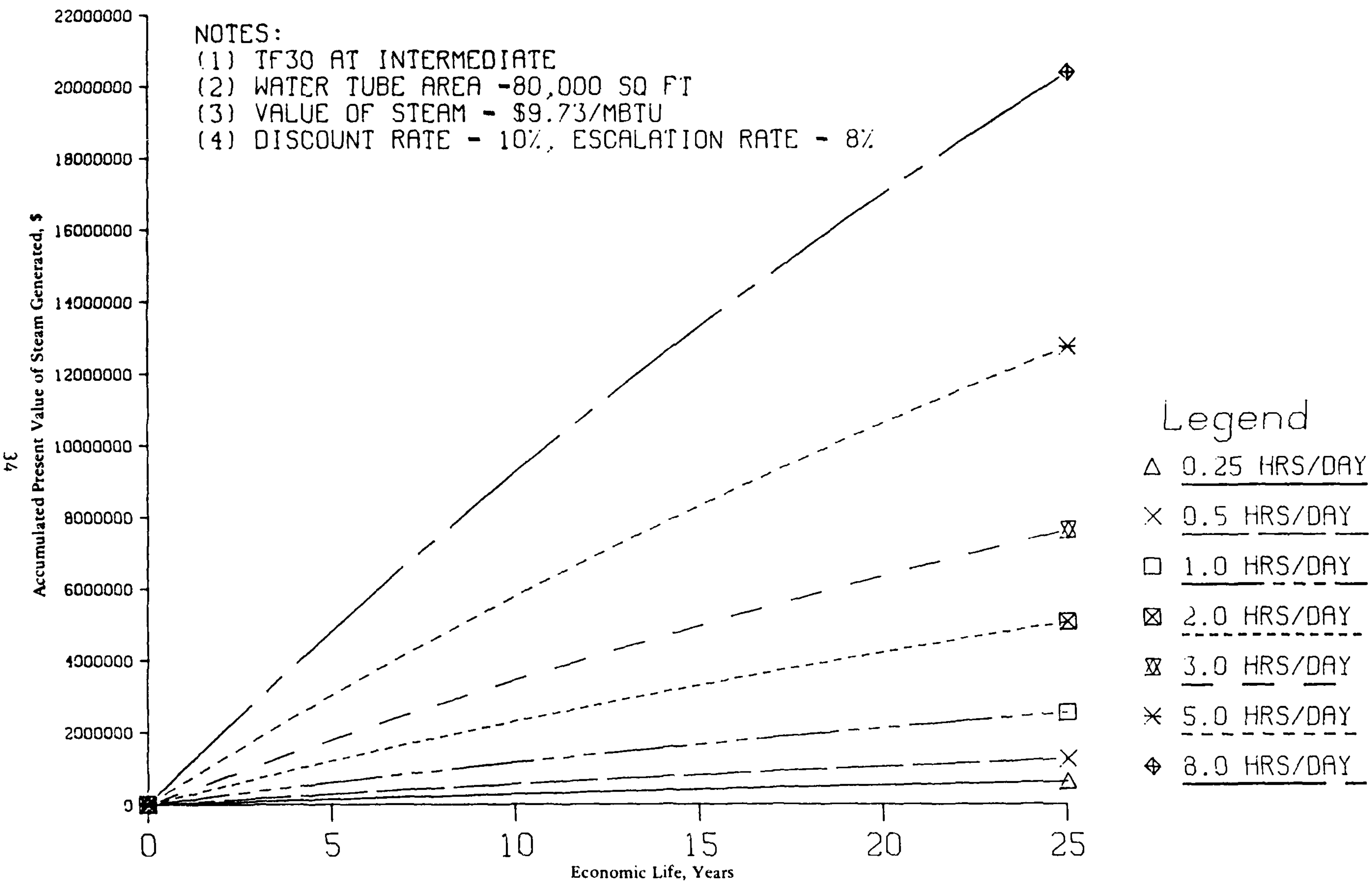

Figure 16. Steam generation in a typical mid-sized gas turbine test cell by using water tubes located at augmenter exit.

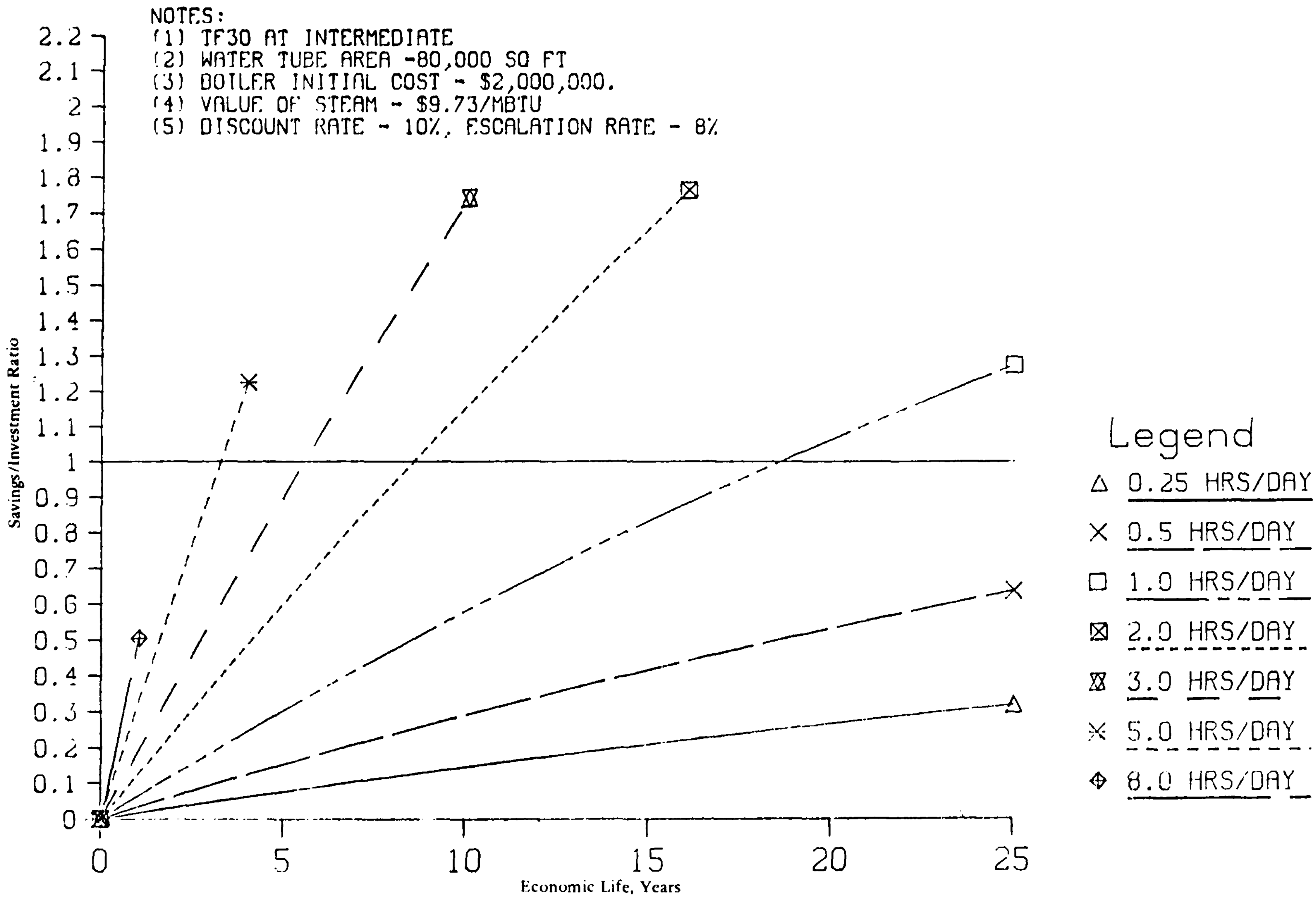

Figure 17. Economics of energy recovery from a typical mid-sized gas turbine test cell by using water tubes located at augmenter exit.

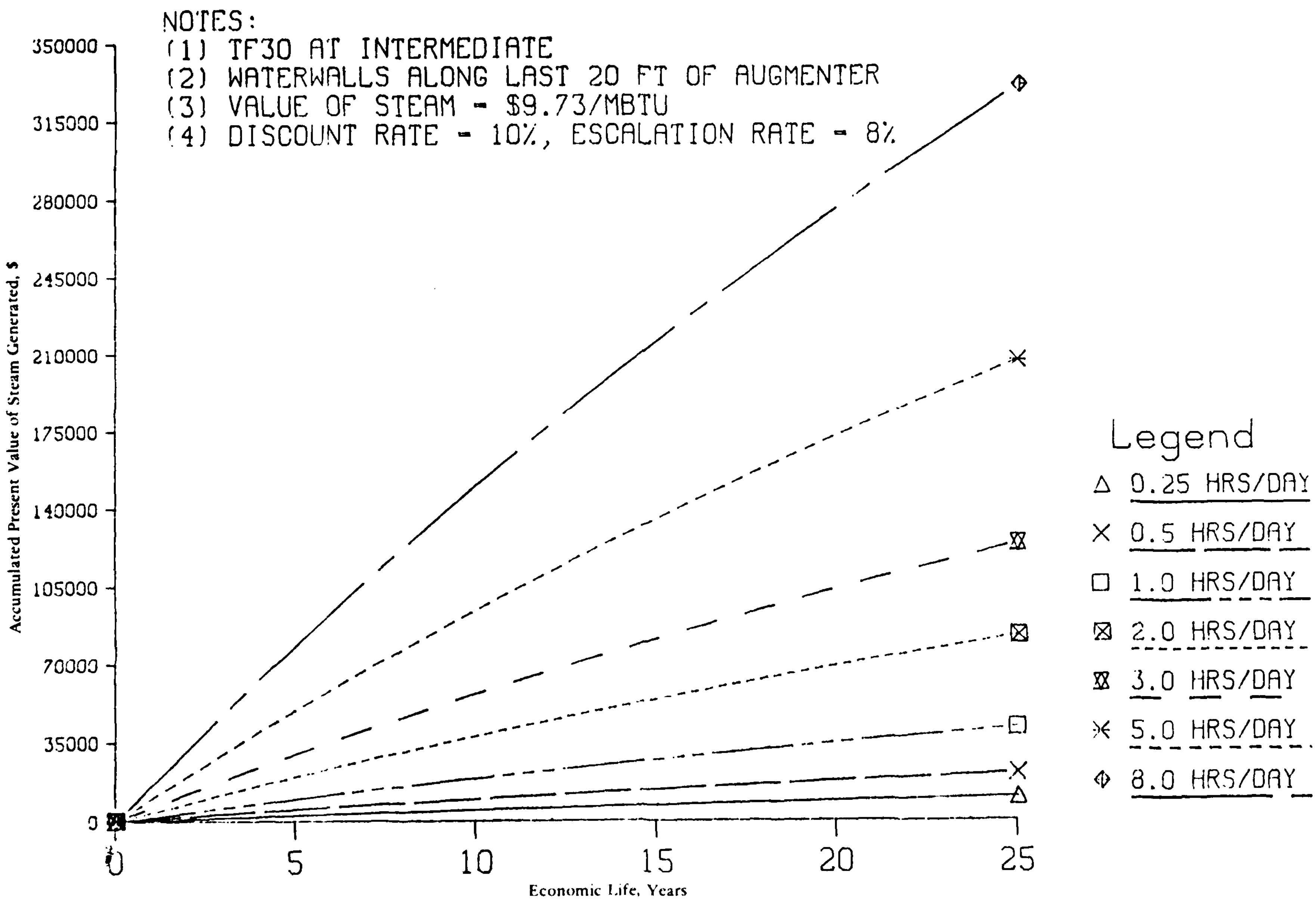

Figure 18. Steam generation in a typical mid-sized gas turbine test cell with waterwalls.

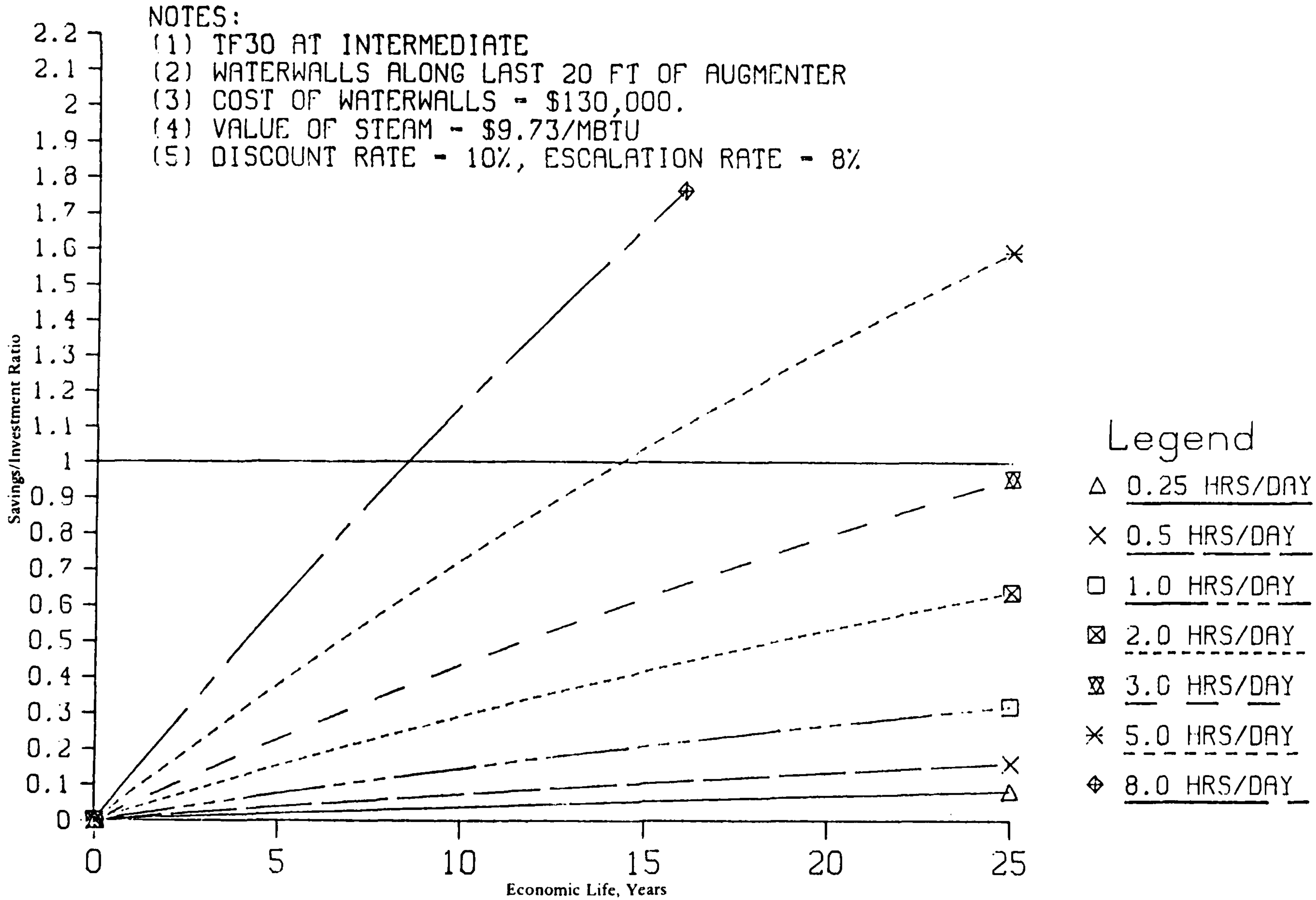

Figure 19. Economics of energy recovery from a typical mid-sized gas turbine test cell with waterwalls.

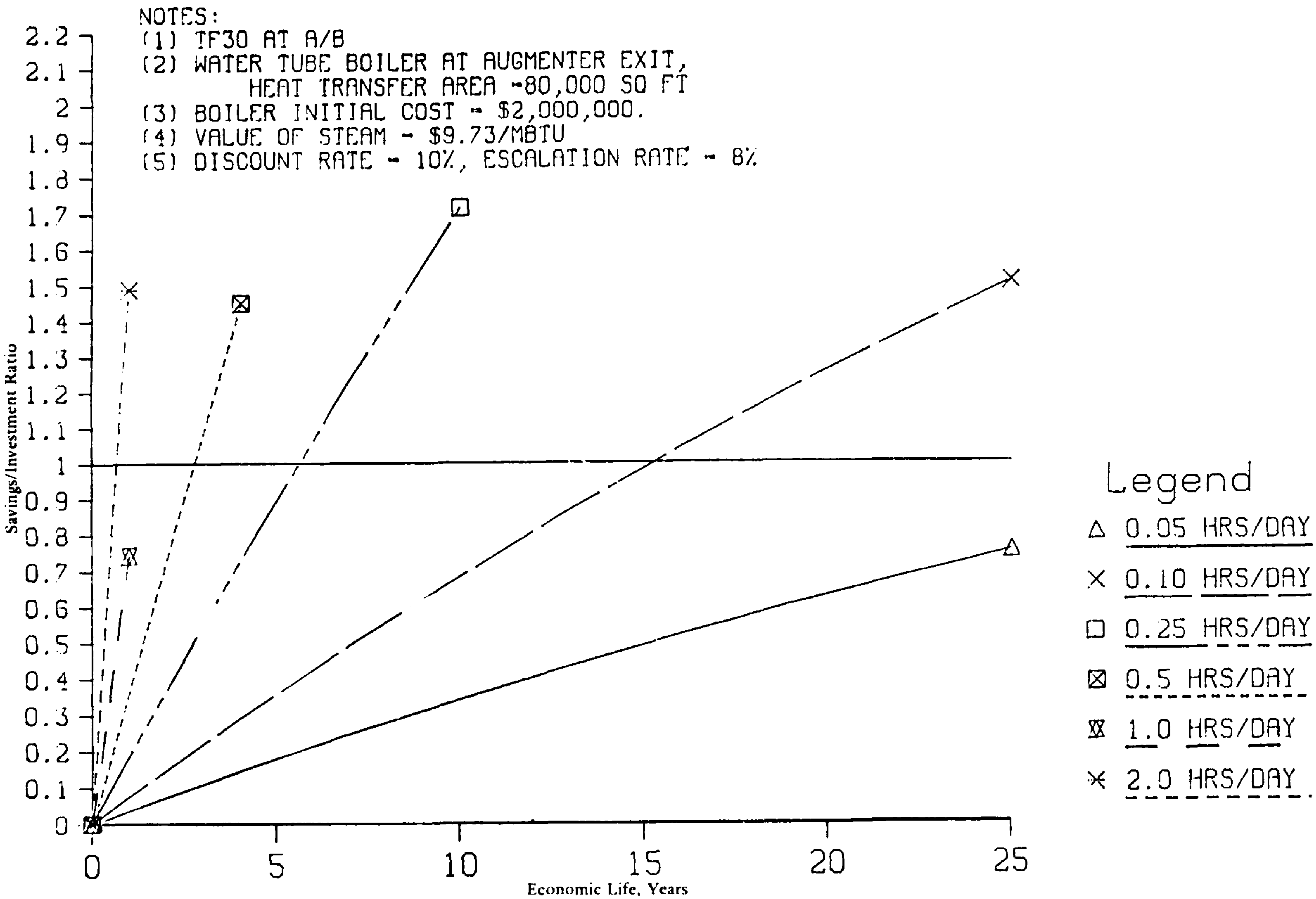

Figure 20. Effect of afterburning on the economics of energy recovery from a typical mid-sized gas turbine test cell.

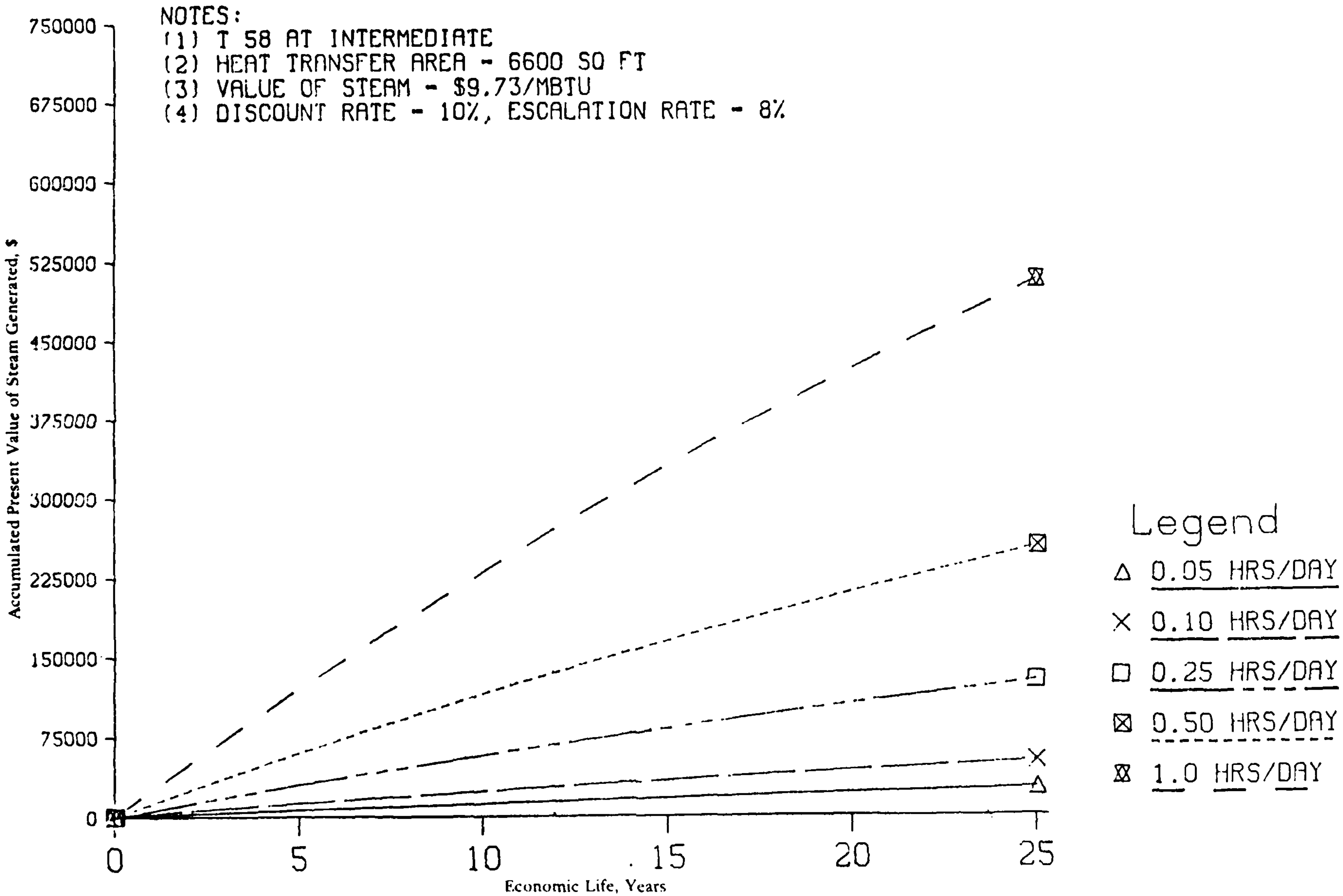

Figure 21. Steam generation in a typical small gas turbine test cell using water tubes at the augmenter exit.

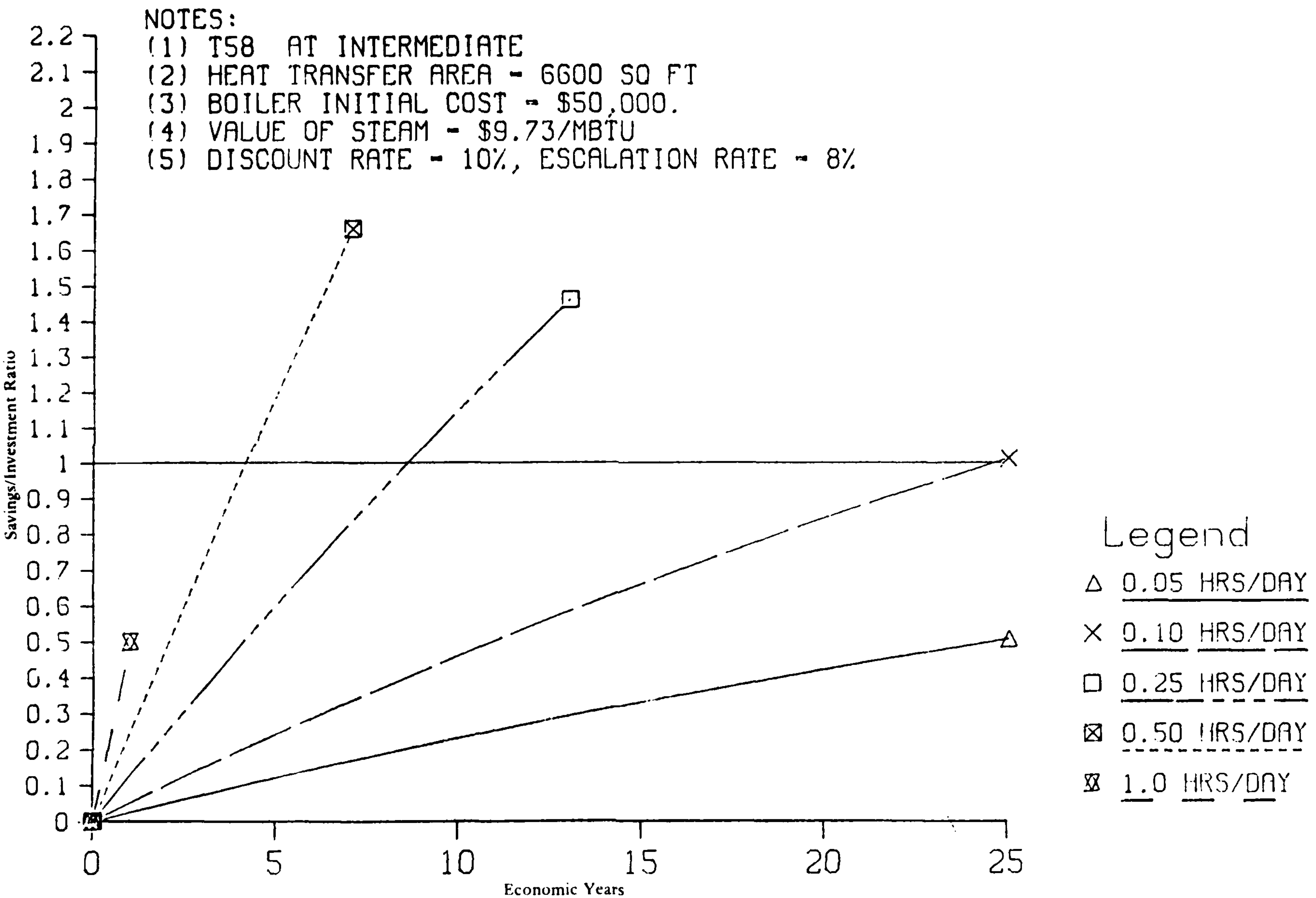

Figure 22. Economics of energy recovery from a typical small gas turbine test cell using water tubes at the augmenter exit.

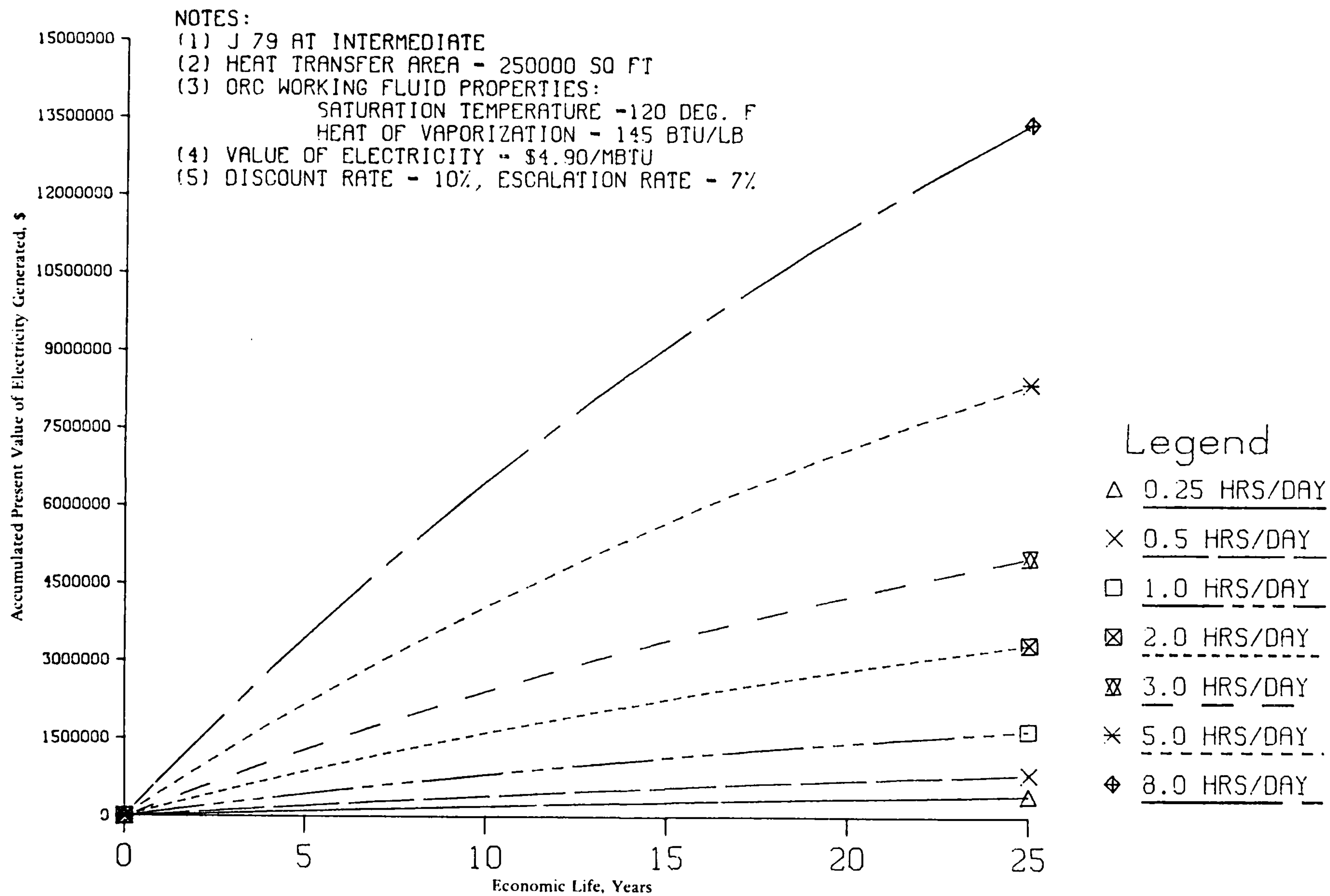

Figure 23. Generation of electricity from thermal energy recovered in a typical large gas turbine test cell using water tubes at the augmenter exit.

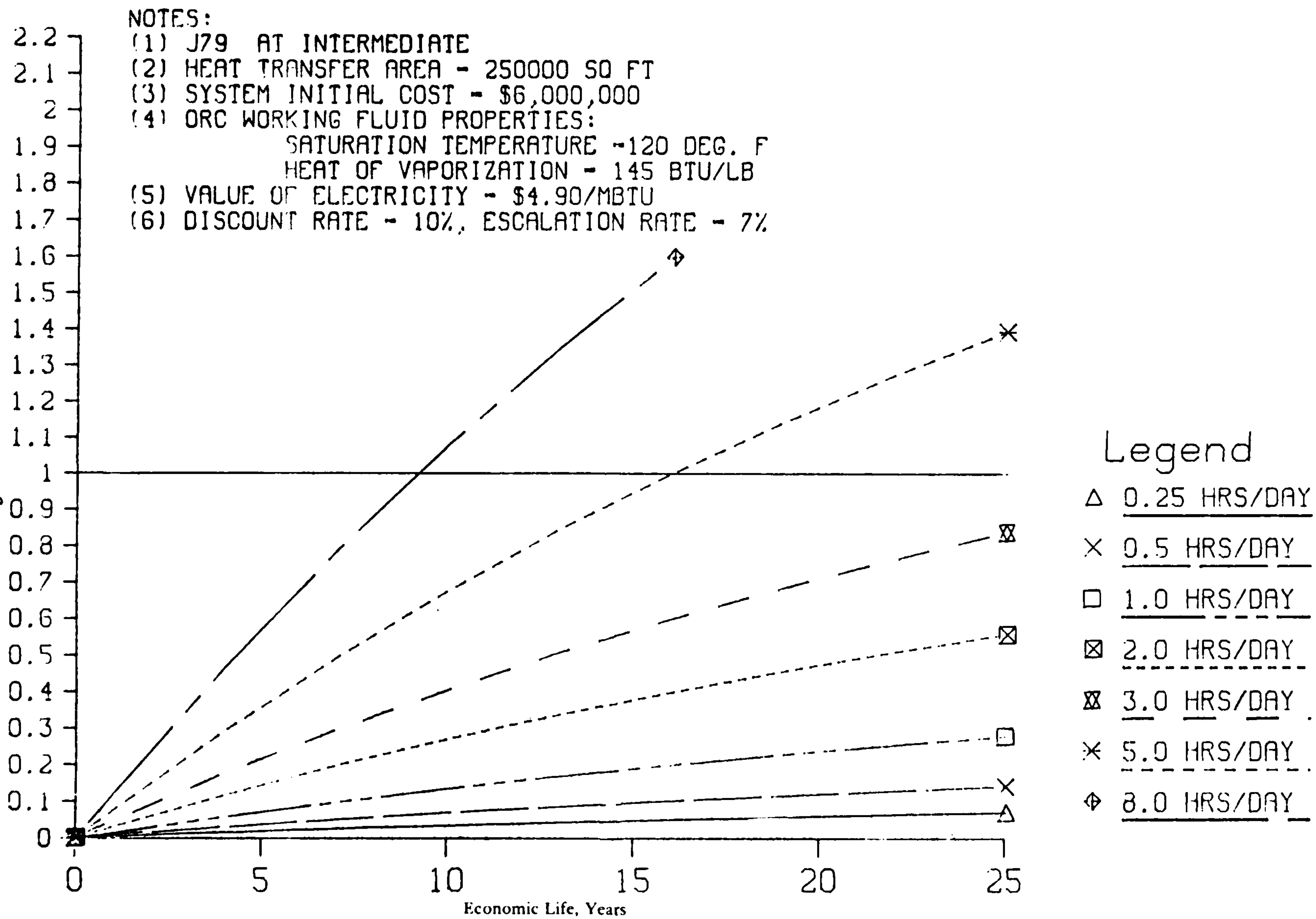

Figure 24. Economics of electricity generation from thermal energy recovered in a typical large gas turbine test cell using water tubes at the augmenter exit.

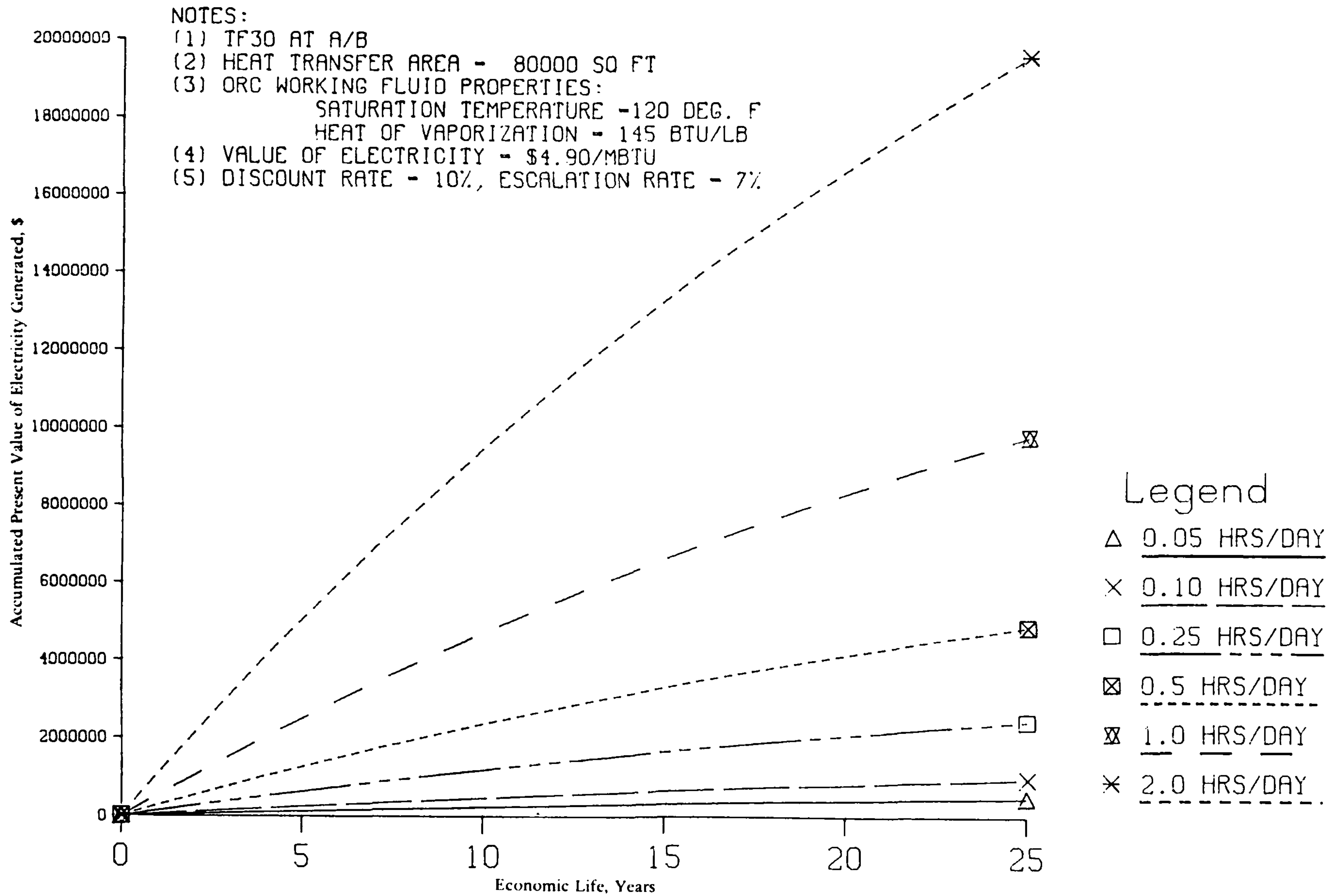

Figure 25. Generation of electricity from thermal energy recovered in a typical mid-sized gas turbine test cell using water tubes at the augmenter exit.

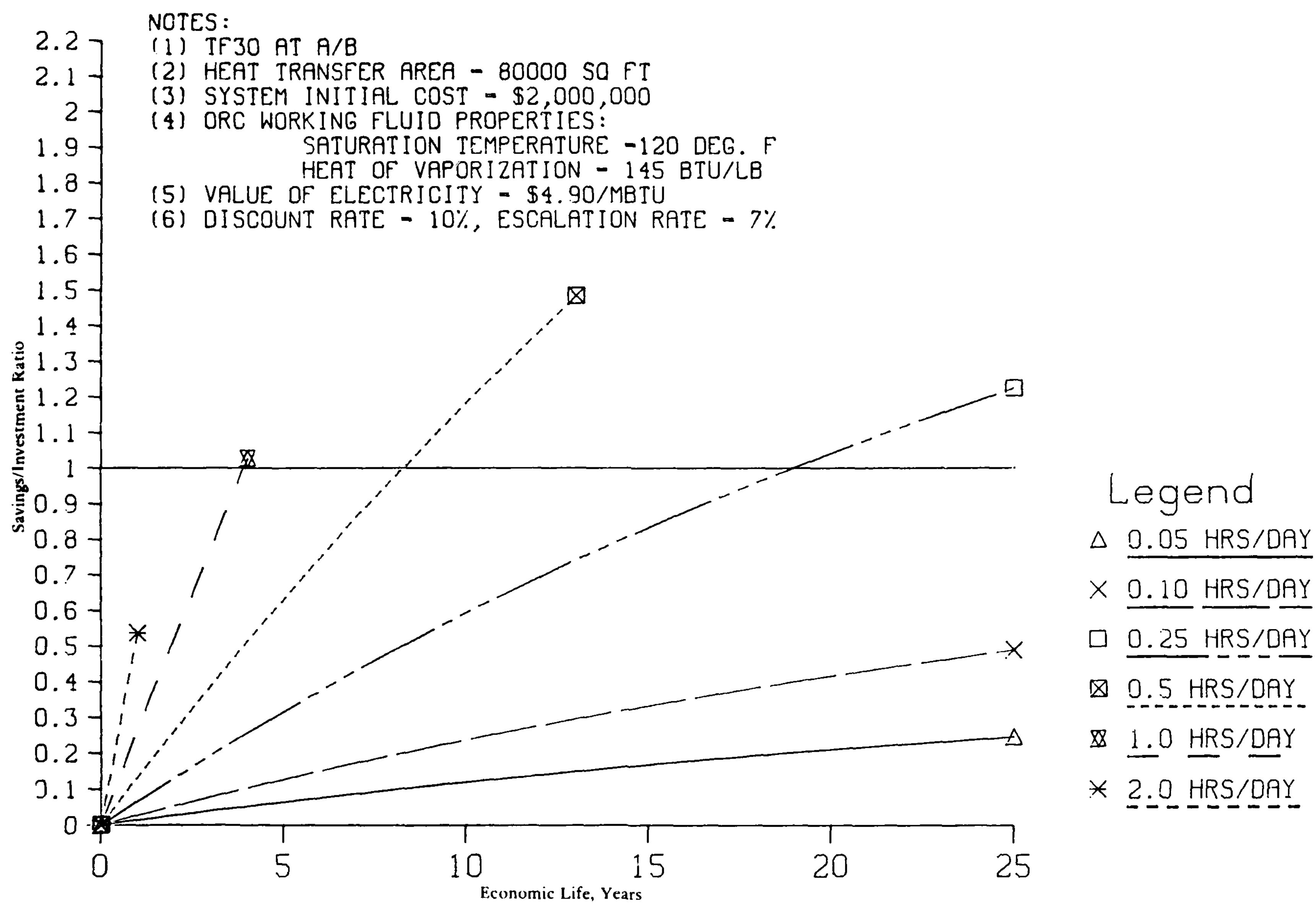

Figure 26. Economics of electricity generation from thermal energy recovered in a typical mid-sized gas turbine test cell using water tubes at the augmenter exit.

Appendix A

SIMULATION OF A JET ENGINE TEST CELL AUGMENTER TUBE

The problems inherent in simulating the operation of test cell augmenter tubes are extremely complex. Re-examine Figure 1 and consider the following augmenter characteristics: multiple, nonconcentric flows at different velocities; turbulence; flow separation; all three modes of heat transfer, simultaneously; extreme changes in temperature and, thus, variable properties; and nonsymmetric three-dimensional geometries. In addition, some tests are of short duration, resulting in a highly transient situation; e.g., testing with afterburners might involve 30-second cycles with 3,000°F exhaust. These complexities lead to a transient, nonlinear problem with coupled energy, mass, and momentum transfer.

To make an augmenter simulation attainable, assumptions are necessary. For this present work, the emphasis is on heat transfer. Can enough steam be generated, via energy transferred from the jet exhaust, to warrant the purchase of a boiler? The modelling tactics will be to simulate the fluid flow (mass and momentum) empirically but use first principles to determine heat transfer. For this plan-of-attack, the following assumptions are made:

1. Flows are one-dimensional, passing through a cylindrical augmenter

2. Steady state, steady flow is stipulated

3. Both the jet and augmentation air are ideal gases

4. Flow within the jet and within the augmentation air can be considered turbulent and perfectly mixed

5. Pressure gradients along the augmenter are negligible compared with temperature gradients and can be neglected

6. The jet nozzle is located exactly at the inlet to the augmenter tube

7. The augmenter walls are black, the jet is gray, and the augmentation air is transparent to thermal radiation

8. Axial radiation along the jet has a negligible effect on temperatures; all radiation is from jet to wall or from wall to wall

9. Heat transfer between the jet and the augmentation air is negligible compared with enthalpy changes due to mixing

10. Radiation from the jet to any heat exchanger located past the augmenter exit is negligble

The validity of several of the assumptions and the accuracy of the resulting simulation are discussed in a subsequent section.

SIMULATING THE JET EXHAUST

The jet is empirically modelled using the curve fits of Becker et al. (Ref 2). Their data are from cold jets, and their test rig is smaller than test cells, necessitating some modification to the empirical constants. Specifically, these relationships have been adjusted to be able to predict the arrival of the jet to the wall at locations observed experimentally at the hush houses, NAS Miramar (Ref 3 and 4).

Following Becker's technique, jet flow geometry is extrapolated from the NAS Miramar data by means of a nondimensional similarity parameter usually referred to as the Craya-Curtet number, C_t, a ratio of the kinematic to dynamic mean inlet velocities,

$$C_t \equiv \frac{r^{*2}V_{JET}(0) + (1-r^{*2})V_{SEC}}{\left\{r^{*2}V_{JET}(0) + (0.5-r^{*2})V_{SEC}^2 - 0.5\left[r^{*2}V_{JET}(0) + (1-r^{*2})V_{SEC}\right]^2\right\}^{1/2}} \quad \text{. . . . . (A-1)}$$

where: r^* = ratio of jet nozzle area to cross-sectional area of the augmenter tube

$V_{JET}(0)$ = velocity of jet at the augmenter inlet

V_{SEC} = velocity of augmentation (secondary) airflow

Then, for $0 < C_t \leqq 0.7$,

$$R_{JET}(Z) = R_{JET}(0) + 0.131\ Z \left\{1 - \left[Z/(Z_R\ R_{AUG})\right]^{5/3}\right\} \quad \text{(A-2)}$$

where: $Z_R \equiv 4.07 \exp(3.54\ C_t)$

$R_{JET}(Z)$ = radius of jet at a distance Z from the augmenter inlet

R_{AUG} = radius of augmenter tube

and for $0.7 < C_t$,

$$R_{JET}(Z) = R_{JET}(0) + 0.126\ Z \quad \text{(A-2')}$$

The geometry of the jet is fully defined by Equations A-1 and A-2. Although it appears that fluid properties are being neglected, it should be noted that the augmentation airflow rate is input directly, rather than calculated. This partially introduces properties of both the jet and augmentation air through the variable V_{SEC}.

A final flow relationship is acquired by employing the assumptions of an isopiestic ideal gas

$$\rho\ T = \text{constant} \tag{A-3}$$

where: ρ = density

T = gas temperature

SIMULATING THE HEAT TRANSFER

To model the heat transfer, the augmenter tube is first divided into axial segments, with the jet, augmentation flow, and inner and outer liner* sections lumped separately as illustrated on Figure A-1. Temperature is assumed constant throughout each section-segment; flows are perfectly mixed.

Mass flow rates through each segment are determined from the geometry of the jet; i.e., from Equation A-2.

$$\Delta\dot{M}_I = \pi\ \rho_{SEC,I}\ V_{SEC,I} \left(R^2_{JET,I} - R^2_{JET,I-1}\right)$$

$$\dot{M}_{JET,I+1} = \dot{M}_{JET,I} + \Delta\dot{M}_I$$

$$\dot{M}_{SEC,I+1} = \dot{M}_{SEC,I} - \Delta\dot{M}_{I+1}$$

where: $\Delta\dot{M}_I$ = augmentation flow entrained by the jet in segment "I"

$\dot{M}_{JET,I}$ = mass flow rate of jet through segment "I"

$\dot{M}_{SEC,I}$ = mass flow rate of augmentation air through segment "I"

$\rho_{SEC,I}$ = density of augmentation air

$R_{JET,I}$ = radius of segment "I" of the jet

Conservation of energy is then applied to each segment of each section. For the jet exhaust (see Figure A-2),

*Some augmenters do not have liners but are of solid construction. For this configuration, the inner and outer "liners" in the model represent the inside and outside of the wall.

$$\dot{M}_{JET,I+1}\left(h_{JET,I+1} - h_{REF} + \frac{V^2_{JET,I+1}}{2}\right) + \dot{q}_{RAD,I,JET\rightarrow IL}$$

$$- \dot{M}_{JET,I}\left(h_{JET,I} - h_{REF} + \frac{V^2_{JET,I}}{2}\right)$$

$$- \Delta\dot{M}_{I}\left(h_{SEC,I} - h_{REF} + \frac{V^2_{SEC,I}}{2}\right) = 0$$

or, using the ideal gas approximation after applying conservation of mass to eliminate the reference enthalpies,

$$\dot{M}_{JET,I+1}\left(C_{P,JET,I+1}\, T_{JET,I+1} + \frac{V^2_{JET,I+1}}{2}\right) + \dot{q}_{RAD,I,JET\rightarrow IL}$$

$$- \dot{M}_{JET,I}\left(C_{P,JET,I}\, T_{JET,I} + \frac{V^2_{JET,I}}{2}\right)$$

$$- \Delta\dot{M}_{I}\left(C_{P,SEC}\, T_{SEC,I} + \frac{V^2_{SEC,I}}{2}\right) = 0$$

where: $T_{JET,I}$ = temperature of jet in segment "I"

$C_{P,JET,I}$ = specific heat of the jet exhaust in segment "I"

$T_{SEC,I}$ = temperature of augmentation air in segment "I"

$C_{P,SEC,I}$ = specific heat of augmentation air in segment "I"

The radiation from jet segment "I" to the wall, $\hat{q}_{RAD,I,JET\rightarrow IL}$, is determined by summing the net radiation between this segment and all sections of the wall,

$$\dot{q}_{RAD,I,JET\rightarrow IL} = \sum_{J=1}^{N} \sigma\, A_{JET,I}\, F_{I,J}\left(\varepsilon\, T^4_{JET,I} - \alpha\, T^4_{IL,J}\right)$$

where: $T_{IL,J}$ = temperature of augmenter inner liner segment "J"

$A_{JET,I}$ = surface area of jet segment "I"

σ = Stefan-Boltzmann constant

$F_{I,J}$ = shape factor for radiation from jet segment "I" to inner liner segment "J"

ε = $\varepsilon(I, T_{JET,I})$ = emissivity of jet segment "I"

α = absorptivity of jet segment "I"

= $\varepsilon(T_{JET,I}/T_{IL,J})^{0.5}$ (Ref 6)

N = number of axial segments of the augmenter tube

For the augmentation airflow (see Figure A-3),

$$\dot{M}_{SEC,I+1}\left(C_{P,SEC}\,T_{SEC,I+1} + \frac{V^2_{SEC,I+1}}{2}\right)$$

$$+ \Delta\dot{M}_{I+1}\left(C_{P,SEC}\,T_{SEC,I+1} + \frac{V^2_{SEC,I+1}}{2}\right)$$

$$- \dot{M}_{SEC,I}\left(C_{P,SEC}\,T_{SEC,I} + \frac{V^2_{SEC,I}}{2}\right) + \dot{q}_{CONV,I,IL\rightarrow SEC} = 0 \qquad \text{(A-5)}$$

where: $\dot{q}_{CONV,I,IL\rightarrow SEC}$ = convection heat transfer from the inner liner to augmentation air segment "I"

h = $\hat{h}A_{AUG}\,(T_{IL,I} - T_{SEC,I})$

$\hat{h}$ = $\hat{h}\,(I, V_{SEC,I})$ = convective film coefficient of segment "I"

A_{AUG} = $A_{AUG,I}$ = surface area of liner in contact with augmentation air segment "I"

Conservation of energy across segments of the inner and outer liners are handled in a similar manner. For the inner liner,

$$\dot{q}_{COND,I\to I-1,IL} + \dot{q}_{COND,I,IL\to OL} + \dot{q}_{CONV,I,IL\to SEC}$$

$$+ \dot{q}_{RAD,I\to J,IL} - \dot{q}_{COND,I+1\to I,IL} - \dot{q}_{RAD,I,JET\to IL} = 0 \qquad \text{(A-6)}$$

where: $\dot{q}_{COND,I\to I-1,IL}$ = conduction along the inner liner

$= kA_{IL}(T_{IL,I} - T_{IL,I-1})/\Delta Z$

$\dot{q}_{COND,I,IL\to OL}$ = conduction between inner and outer liners

$\dot{q}_{RAD,I\to J,IL}$ = radiation between different segments of the inner liner

$$\dot{q}_{RAD,I\to J,IL} = \sum_{J=1}^{N} \sigma\, A_{AUG}\, Fl_{I,J}(1 - \varepsilon)\left(T^4_{IL,I} - T^4_{IL,J}\right)$$

where: $Fl_{I,J}$ = shape factor for radiation from inner liner segment "I" to inner liner segment "J"

k = effective coefficient of thermal conductivity, includes liner, acoustic pillows, concrete, etc. (where applicable)

A_{IL} = cross sectional area of inner liner, acoustic pads, etc.

ΔZ = spacing between nodes

Finally, for the outer liner,

$$\dot{q}_{COND,I\to I-1,OL} + \dot{q}_{CONV,I,OL\to\infty} - \dot{q}_{COND,I+1\to I,OL}$$

$$- \dot{q}_{COND,I,IL\to OL} = 0 \qquad \text{(A-7)}$$

where: $\dot{q}_{CONV,I,OL\to\infty}$ = convection heat transfer off outer skin of augmenter

$= \hat{h}_\infty A_\infty\,(T_{OL,I} - T_\infty)$

Equations A-4 through A-7 for all sections, along with Equation A-3 and the Equation of Continuity, are solved simultaneously to determine temperatures throughout the augmenter assembly. When the jet reaches the wall, conservation of augmentation flow energy is deleted, and the

other equations are modified accordingly. Due to the nonlinearities, an iterative technique is necessary, and the Gauss-Seidel method, with relaxation, is employed for this purpose. Figure A-4 illustrates typical predicted augmenter temperature profiles.

The heat transfer characteristics perhaps need further discussion. Radiation was modelled by considering each jet segment as a separate gas mass and applying the mean beam length approximation suggested by Hottel (Ref 6). With this approximation, radiation from irregular geometries is related to radiation from a gas hemisphere by extrapolation using a fictitious dimension called the mean beam length.

Emissivity of the jet is a function of its geometry (mean beam length), composition, and temperature. Geometry is easily acquired from the node spacing and from Equation A-2. Composition of each segment is determined by inputting the weight fraction of the radiators, CO_2, H_2O, and CO, at the engine nozzle and then progressively diluting the jet with augmentation air. Temperature is the problem; the interdependency with temperature necessitates including the emissivity calculations in the temperature iteration. The gas emissivity data of Hottel were curve-fitted to provide a continuous relationship as a function of mean beam length, composition, and temperature. Figure A-5 shows typical emissivities calculated in this manner.

Very little work has been done in the area of convection heat transfer to confined jets. Kang et al. (Ref 7) have experimentally determined some Nusselt numbers, but their tests are not comprehensive enough to provide the foundation for any correlation. Thus, conventional relationships (Ref 8) for turbulent flow through a cylinder had to be employed, substituting the equivalent diameter of the augmentation flow for the diameter of the cylinder,

$$\hat{h} = \frac{14\ k_{SEC}}{D_{EQV}^{0.2}} \left(\frac{V_{SEC}\ \rho_{SEC}}{\mu_{SEC}} \right)^{0.8}$$

where: $\hat{h}$ = film coefficient of convective heat transfer between augmentation airflow and the inner liner

k_{SEC} = thermal conductivity of augmentation air

μ_{SEC} = viscosity of augmentation air

D_{EQV} = equivalent diameter of augmentation flow

= $2\ (R_{AUG} - R_{JET})$

This convection coefficient varies with equivalent diameter of the augmentation flow and, therefore, varies from segment to segment. Properties of the augmentation flow vary with temperature, requiring the film coefficient calculations to also be included in the iteration. Figure A-6 shows typical calculated coefficients.

BOILER SIMULATION

To simulate waterwalls, the temperature of the outer liner is set equal to the saturation temperature of the steam; and all heat resistance, except the metal, is removed from between the two liners. This is equivalent to neglecting the resistance to heat transfer on the boiling water side of the walls, a good approximation since this resistance is several orders of magnitude less than the resistance to convection and radiation from the jet exhaust. The steam generation is then determined directly from a summation of the energy transferred to the outer liner.

Simulation of convection, water tube boilers is more difficult. Conservation of energy is applied to the jet and augmentation flow through the heat exchanger, to the water/steam flow through the heat exchanger, and to the overall heat exchanger. These relationships are, in the same order,

$$\dot{q}_{STM} = \dot{M}_{GAS}\ C_{P,GAS}(T_{GAS} - T_{STACK}) \tag{A-8}$$

$$\dot{q}_{STM} = \dot{M}_{STM}\ \Delta h_{fg} \tag{A-9}$$

$$\dot{q}_{STM} = UA\ \Delta T_{M} \tag{A-10}$$

where: $\dot{M}_{GAS}$ = sum of jet and augmentation air

$\dot{M}_{STM}$ = steam generation

$\dot{q}_{STM}$ = heat transferred from jet and augmentation airflow to the steam

T_{GAS} = temperature of gas entering the boiler

T_{STACK} = temperature of gas exiting the boiler

UA = product of boiler overall heat transfer coefficient and heat transfer area

Δh_{fg} = heat of vaporization of steam

ΔT_m = logarithmic mean temperature difference

where:
$$\Delta T_m \equiv \frac{T_{GAS} - T_{STM}}{\ln\left(\dfrac{T_{GAS} - T_{STM}}{T_{STACK} - T_{STM}}\right)}$$

T_{STM} = saturation temperature of steam

resulting in Equations A-8, A-9, A-10 and the four unknowns: $\dot{q}_{STM}$, $\dot{M}_{STM}$, T_{STACK}, and UA. The final relationship is determined by stipulating a boiler effectiveness*, e,

$$e \equiv \frac{T_{GAS} - T_{STACK}}{T_{GAS} - T_{STM}}$$

If boiler effectiveness is known, steam generation and the other unknowns can be calculated. Furthermore, if the boiler tube configuration is also stipulated, the heat transfer characteristics can be estimated. For example, if the boiler is to be of a staggered tube configuration (Ref 8),

$$U \approx \hat{h}_{TUBE} = 0.287 \frac{k_{JET}}{D_{TUBE}}\left(\frac{\rho_{JET}\, V_{JET}\, D_{TUBE}}{\mu_{JET}}\right)$$

*A value e = 0.76 is assumed throughout these analyses.

where: $\hat{h}_{TUBE}$ = convection film coefficient between jet exhaust and water tubes

D_{TUBE} = outer diameter of water tubes

It should be noted that the resistance to heat transfer through the tube walls and to the boiling water are being neglected. With this equation, an estimate of boiler heat transfer area is also acquired because UA is known. Properties are determined by assuming the jet exhaust behaves identically to air and applying the Eucken equations (Ref 9),

$$k_{JET}, \mu_{JET} \propto \frac{T_{JET}^{1.5}}{225 + T_{JET}}$$

ACCURACY OF THE AUGMENTER MODEL

To evaluate the simulation, predicted augmenter inner liner temperatures are compared with measured values. The accuracy of these temperatures makes a valid benchmark since they indicate the accuracy of the simulation of heat transfer to the walls and, by supposition, to a waterwall heat exchanger. The same reasoning applies to the augmenter exit gas temperature, but here the modelling involves only simple mixing of gases, and little error is likely. Regardless, these temperatures can be examined concurrently by noting that, due to high wall resistance, there is little difference between gas and wall temperatures near the augmenter exit. This trend is illustrated in Figure A-4.

An abundance of data are not available with which to make this comparison. The hush houses at the NAS Miramar have been studied extensively. These facilities were used to develop the empirical model of the jet exhaust, however. It is suspect to use the same sites to evaluate the model. Nevertheless, they will be used. The hush house at the Marine Corps Air Station El Toro, although studied less extensively, provides a better accreditation.

The comparisons are made on Figures A-7 through A-9. Predicted and measured temperatures are within ±50°F of each other. The exception is the TF30 engine undergoing afterburning tests where the simulation of inner liner temperatures is in error by more than 200°F. Not enough temperatures have been measured near the augmenter inlet to verify the existence of the radiation peaks shown on the figures.

Several sources of error are obvious, each related to the assumptions. First, the hush houses are not cylindrical but elliptical. Although the distance from the nozzle to the nearest augmenter wall was used as an effective radius, the effects of this cross section on flow characteristics could not be accounted for. The steady state assumption is possibly not valid for the afterburning tests which tend to be of short duration. Actual inner liner temperatures could be much higher or much lower than steady state temperatures, depending upon wall thickness, specific heat, and thermal conductivity as well as time. Jet exhaust and secondary entrained air are certainly not perfectly mixed at the nozzle. A hot core of exhaust will survive for some distance, tending to damp out both the radiation peak and convection valley predicted by the model and illustrated on Figures A-7 through A-9. Finally, the jet nozzle is not located exactly at the augmenter inlet but some 10 feet back inside the hush houses.

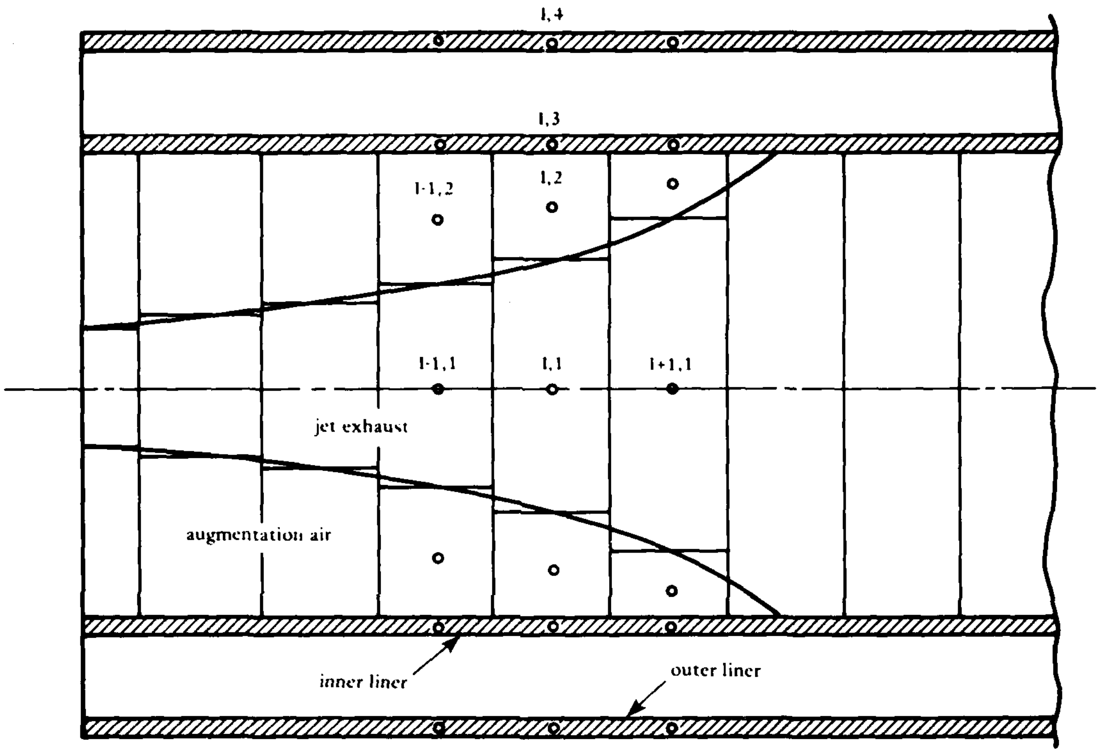

Figure A-1. Dividing the augmenter into segments

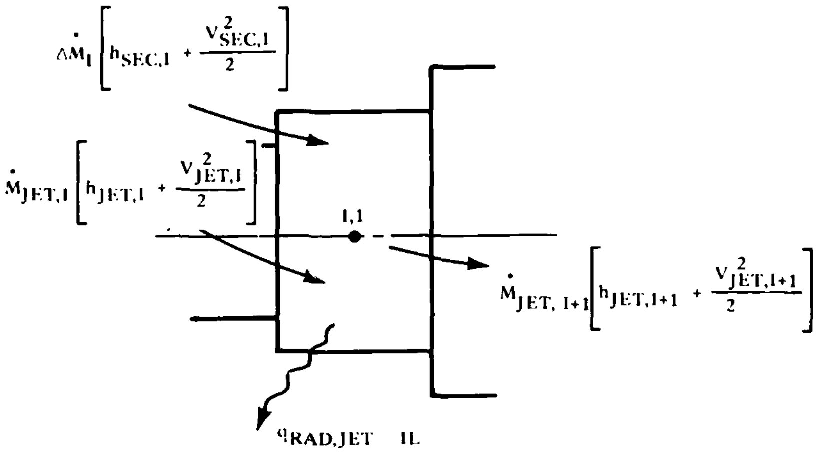

Figure A-2. Conservation of energy across segment of jet exhaust.

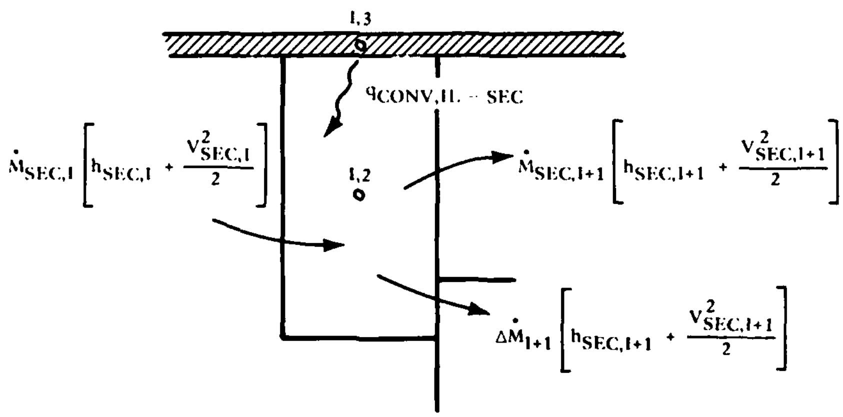

Figure A-3. Conservation of energy across segment of augmentation air.

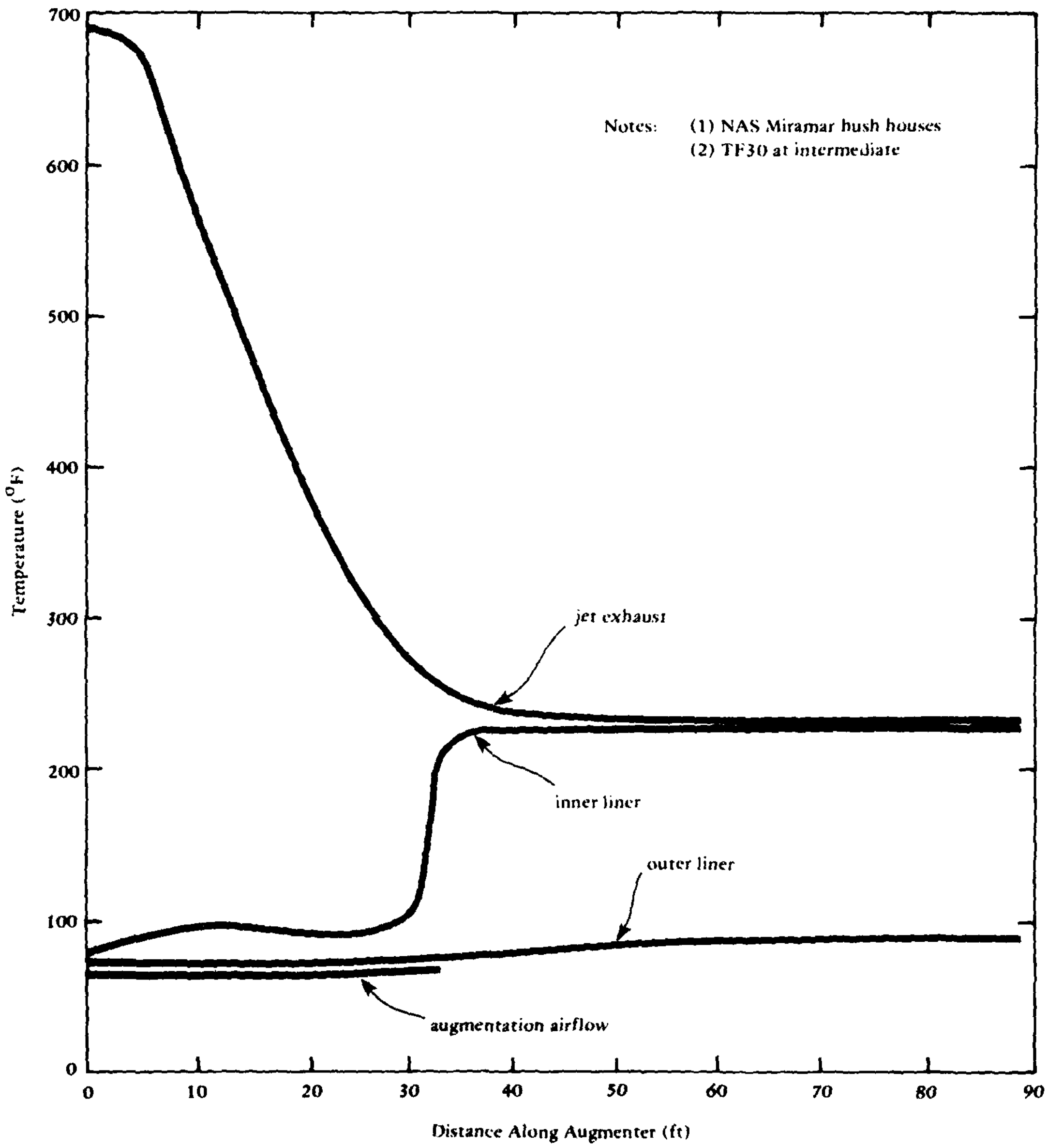

Figure A-4. Typical predicted temperature profiles along the augmenter.

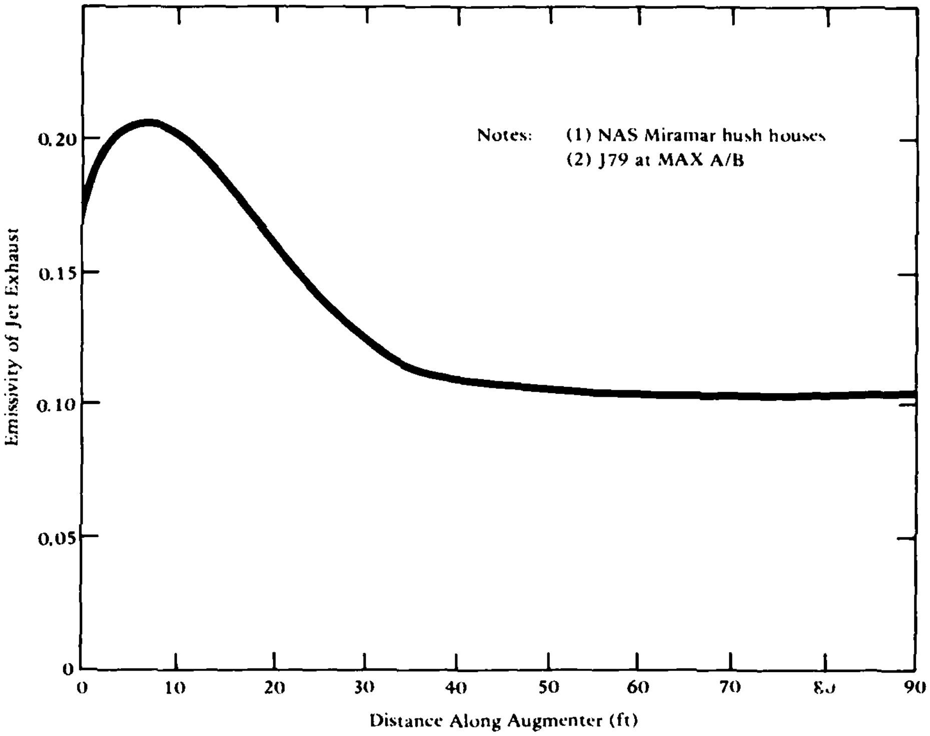

Figure A-5. Typical emissivities of jet exhaust.

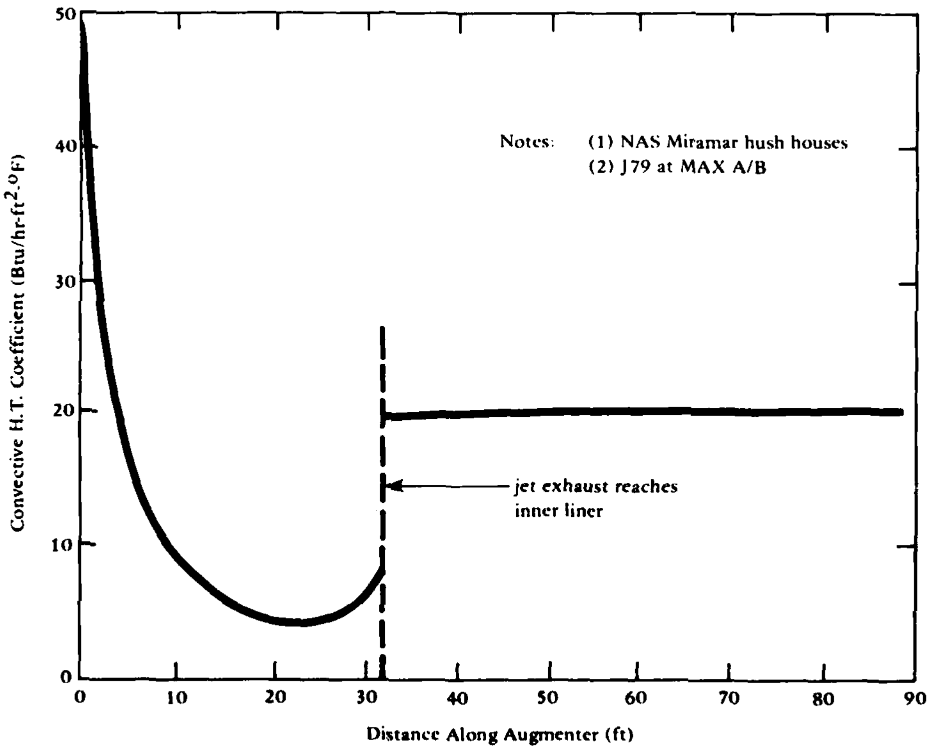

Figure A-6. Typical coefficients of convective heat transfer between inner liner and augmentation airflow.

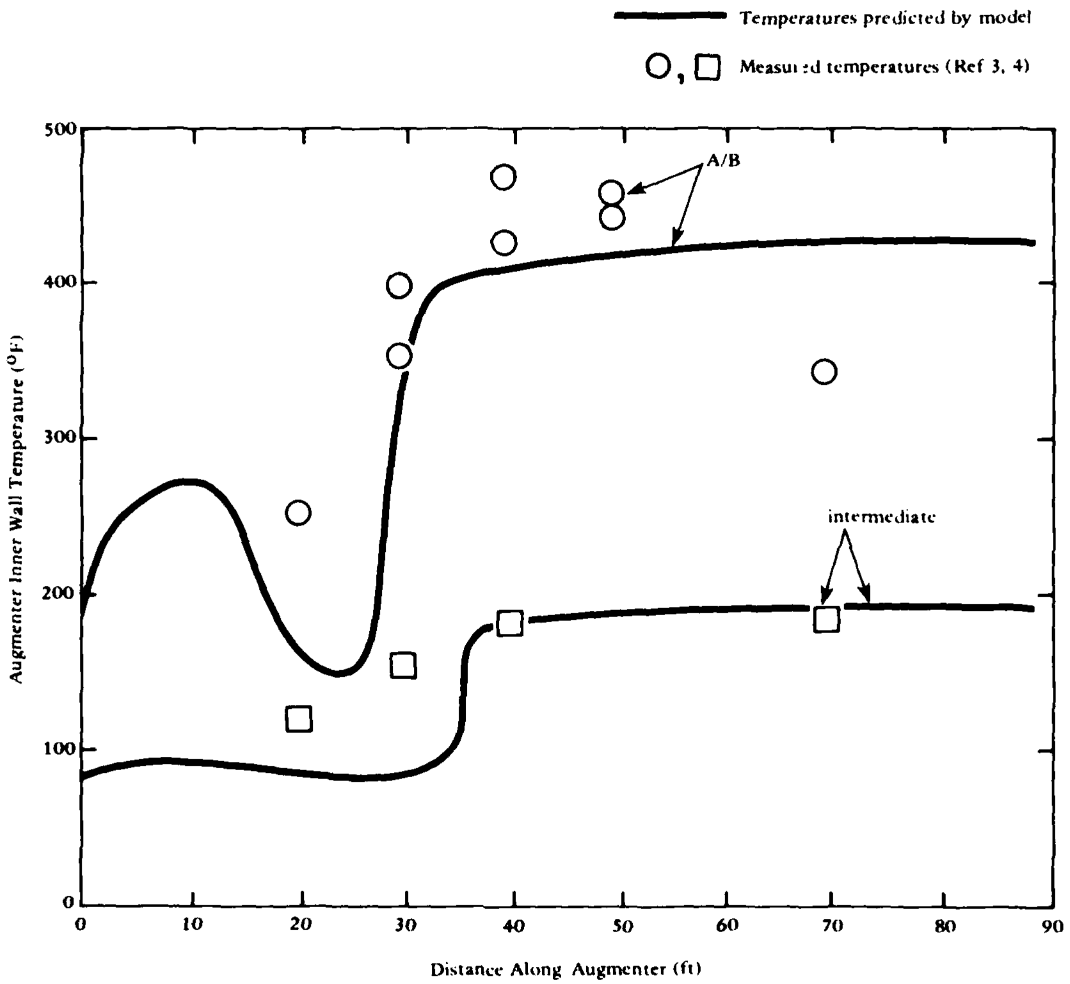

Figure A-7. Evaluation of augmenter model by comparison with temperatures measured during J79 testing in the hush houses at NAS Miramar.

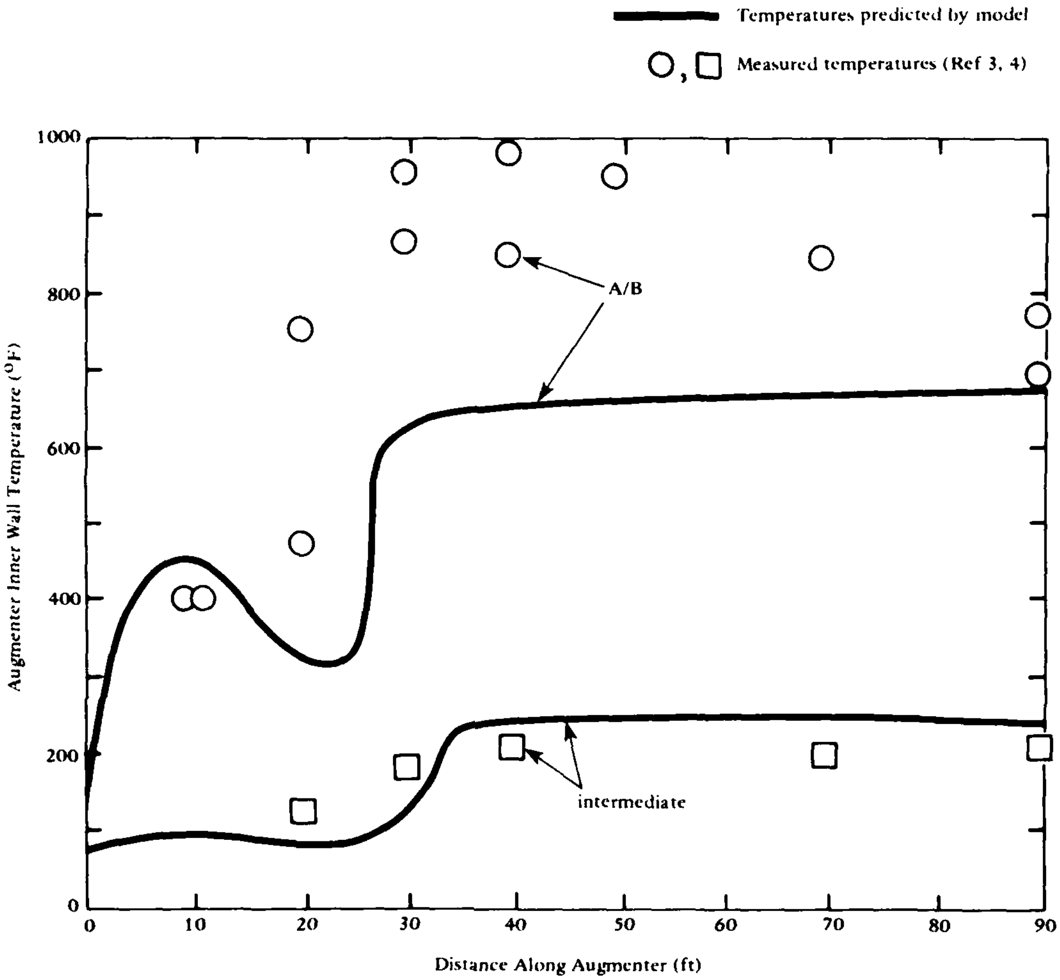

Figure A-8. Evaluation of augmenter model by comparison with temperatures measured during TF30 testing in the hush houses at NAS Miramar.

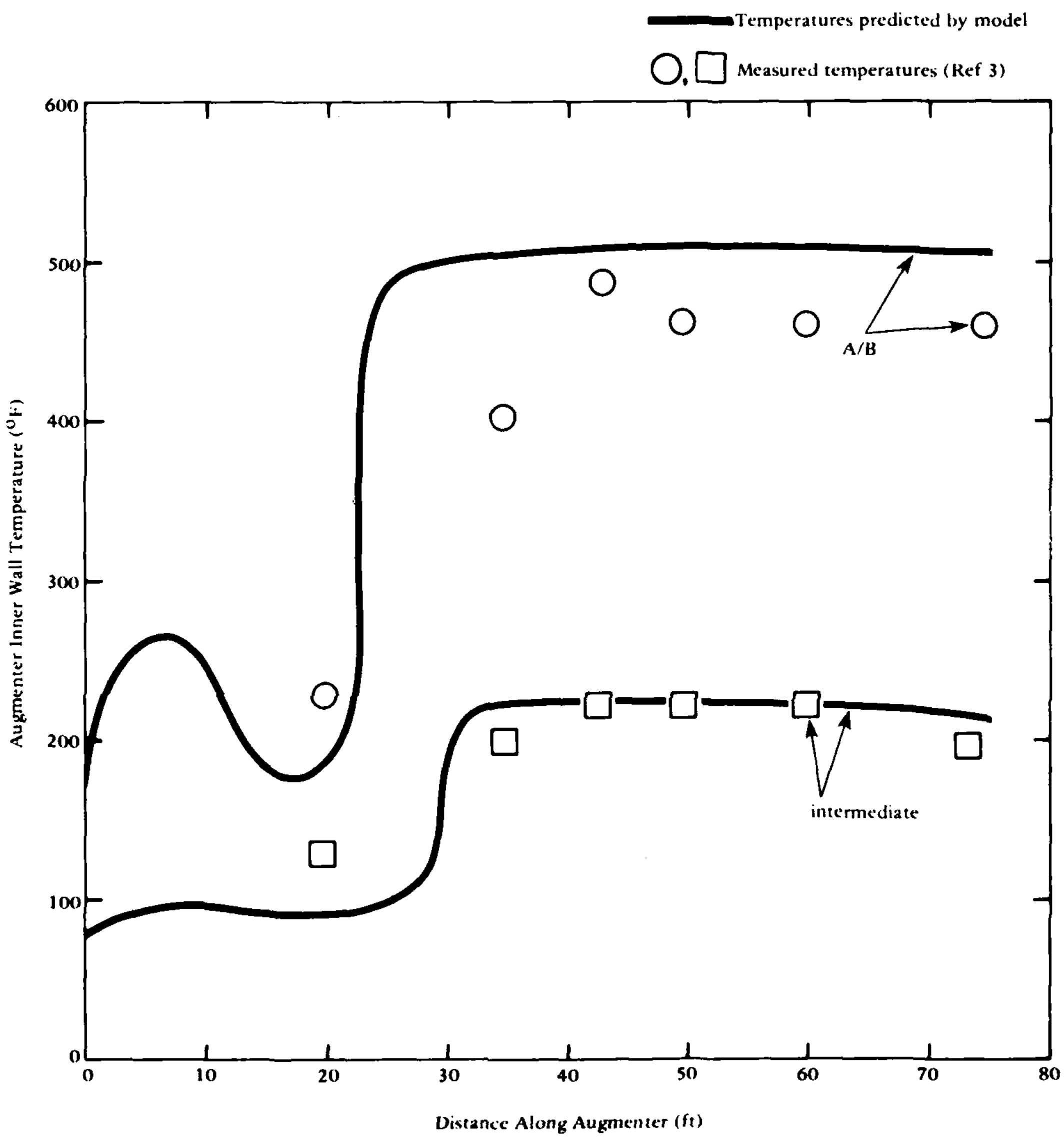

Figure A-9. Evaluation of augmenter model by comparison with temperatures measured during J79 testing in the hush house at MCAS El Toro.

Appendix B

METHOD OF CALCULATING THE ECONOMICS OF TEST CELL ENERGY RECOVERY

Once test cell steam generation has been determined, its value is estimated,

$$\text{VALUE} = \dot{M}_{STM} \times \text{COST} \times \text{TIME} \tag{B-1}$$

where: $\dot{M}_{STM}$ = mass flux of steam generated

COST = assumed value of one unit of steam

TIME = average utilization of the test cell (see Table C-1)

and accumulated over the economic life of the heat exchanger (or life of the test cell, if shorter),

$$PV_{NN} = \sum_{i=1}^{NN} \left[\text{VALUE} \left(\frac{1 + \text{ESC}}{1 + \text{DISC}} \right)^{i} \right] \tag{B-2}$$

where: PV_{NN} = present value of steam generated over a period of NN

ESC = assumed escalation rate of the cost of steam (Ref 5)

DISC = assumed discount rate (Ref 5)

allowing a savings/investment ratio to be predicted,

$$SIR_{NN} = \frac{PV_{NN}}{\text{PRICE}} \tag{B-3}$$

where PRICE is the cost of the waterwalls or heat exchanger.

The economics of the Rankine cycle generation of electricity are analogous, substituting the value of electricity for the value of steam.

COST OF ENERGY RECOVERY HARDWARE

A major obstacle is the determination of PRICE. Very few boilers/heat exchangers large enough for this application are manufactured, and these few are all custom jobs.

To acquire an estimate of the cost of a test cell heat exchanger, twenty boiler manufacturers were asked to provide a preliminary design. Table B-1 describes a water tube heat exchanger composited from their responses. It is presented without documentation. For purposes of applying this design to a particular test cell/engine/power setting, a scaling criterion was developed.

The downstream convection heat exchanger (Configuration No. 1 of Figure 1) cost is ratioed linearly from Table B-1 using the total gas flow as the independent variable,

$$\text{PRICE} = \text{PRICE}_{B1} \left(\frac{\dot{M}_{TOTAL}}{\dot{M}_{TOTAL,B1}} \right) \tag{B-4}$$

where the subscript B1 refers to the values in Table B-1 and TOTAL refers to the sum of the jet and secondary flow. The overall heat transfer coefficient is kept at approximately 9 Btu/hr-ft^2°F, equivalent to a flow velocity of about 80 ft/sec over 2-inch tubes.

When convection heat exchangers are inside the augmenter near the engine nozzle (Configuration No. 4 of Figure 1), the heat transfer area is input directly while the overall heat transfer coefficient is allowed to increase, following the high velocities encountered. The price of the heat exchangers is established in a manner analogous to Equation B-4, using heat transfer area in place of total gas flow,

$$\text{PRICE} = \text{PRICE}_{B1} \left(\frac{A_{TUBES}}{A_{TUBES,B1}} \right) \tag{B-5}$$

This relationship is applied for lack of a better approach. The high gas velocities would be expected to create some serious tube erosion problems, requiring thicker tubes and probably special alloys. In addition, the tubes would have to withstand occasional bursts of A/B. It follows that these heat exchangers would be more expensive than equivalent downstream configurations.

No waterwall designs were submitted in response to the survey of boiler manufacturers. Waterwall areas are input and heat transfer characteristics built into the model, however, neither presents a problem. The use of waterwall prices will be avoided, to the extent possible, in the comparisons. When necessary, Equation B-5 will be employed.*

*Again, for lack of a better approach. This is tantamount to the assumption that the fabrication of the tubes is the major expense in the manufacture of each device.

Table B-1. Composite Heat Exchanger for Energy Recovery From Gas Turbine Engine Test Cell

Type	Convection, Shell and Tube
Gas flow	$2.3\ (10)^6$ lb/hr
Gas temperature in	420°F
Gas temperature out	367°F
Steam flow	30,300 lb/hr
Steam temperature	350°F
Steam pressure	135 psia
Heat transferred	$30\ (10)^6$ Btu/hr
Heat exchanger width	50 ft
Heat exchanger height	15 ft
Heat exchanger length	72 ft
Tube diameter	2 inches
Tube thickness	0.12 inch
Fin segment	0.156 inch
Fin length	0.5 inch
Fin thickness	0.035 inch
Number of fins	6/in.
Number of circuits	45
Number of passes	12
Heat transfer surface	118,000 ft^2
Gas ΔP	5.85 inches H_2O
Cost	$2,000,000.

Appendix C

JET ENGINE TEST CELL CHARACTERISTICS

Table C-1 summarizes the geometries and flow characteristics of test cells used in the analyses. With the exception of the hush houses at the MCAS El Toro, all of these facilities are located in the San Diego area. Geometries and cell utilization were acquired from Reference 10. This reference also describes the cells in greater detail. Flow rates and temperatures were acquired from References 3 and 4. The compositions of the engine exhaust gases at the nozzle were determined by back-calculating from stack gas compositions measured on the Miramar "A" test cell and NARF North Island Test Cell 19 (Ref 11, 12 and 13). It was assumed that the chemical composition of the jet exhaust at the nozzle was dependent only on the type of engine and power setting; the same values were used for the other test cells.

Table C-1. Gas Turbine Engine Test Cell Characteristics

Augmenter Description	Engine Tested	Average Utilization (hr/yr)	Jet Exhaust					Augmentation Airflow (lb/sec)	Comments
			Flow Rate (lb/sec)	Total Temperature (°F)	Composition (% Weight)				
					CO_2	H_2O	CO		
NAS Miramar Hush Houses									
Length: 90.5 ft Effective Diameter: 11 ft[a] Liner: Acoustic pads between inner and outer perforated stainless steel sheets	TF30 at intermediate	150[b]	250	940	2.75	3.0	0.5	1,200	F-14A
	TF30 afterburning	15	250	3,140	16.3	8.15	1.0	1,200	F-14A
	J79 at intermediate	113	180	1,140	4.5	3.75	0.5	1,520	F-4
	J79 afterburning	12	180	3,060	15.9	8.0	1.0	1,520	F-4
	J52 at intermediate	65	140	1,420	--	--	--	--	A-4
MCAS El Toro Hush House									
Length: 67 ft Effective Diameter: 9 ft[a] Liner: Acoustic pads between inner and outer perforated stainless steel sheets	J79 at intermediate	--	180	1,140	4.5	3.75	0.5	1,130	F-4
	J52 at intermediate	--	140	1,420	--	--	--	1,410	A-4
NAS Miramar "A" Test Cell									
Length: 35 ft Effective Diameter: 6 ft Liner: Single perforated steel liner, 6-ft space between liner and noise baffles	TF30 at intermediate	72.9	250	940	2.75	3.0	0.5	410	
	T30 afterburning	62.6	250	3,140	16.3	8.15	1.0	410	
NARF North Island Test Cell 10									
Length: 14 ft[c] Effective Diameter: 2 ft 8 in.[d] Liner: Two stainless steel liners separated by 6 in. of wire rope	T64 at intermediate	66	--	--	--	--	--	--	Helicopter engines

continued

Table C-1. Continued

Augmenter Description	Engine Tested	Average Utilization (hr/yr)	Jet Exhaust					Augmentation Airflow (lb/sec)	Comments
			Flow Rate (lb/sec)	Total Temperature (°F)	Composition (% Weight)				
					CO_2	H_2O	CO		
NARF North Island Test Cell 11									
Length: 43 ft[e] Effective Diameter: 2 ft 6 in.[f]	T58 at intermediate	79	15	1,160	--	--	--	5	Helicopter engines
NARF North Island Test Cell 14									
Length: 27 ft[g] Effective Diameter: 7 ft[h] Liner: Single steel liner, isolated	J79 at intermediate	15.7	180	1,140	--	--	--	300	
	LM2500 at intermediate	80	--	--	--	--	--	--	
NARF North Island Test Cell 19									
Length: 80 ft[g] Effective Diameter: 8 ft[i] Liner: Two steel liners surrounded by 14 inches of concrete, water injection rings near inlet	J79 at intermediate	196.3	180	1,140	--	--	--	470	Test cell 19 scheduled for modernization
	J79 afterburning	17.7	180	3,060	--	--	--	470	
NARF North Island Test Cell 20									
Length: 74 ft Effective Diameter: 13 ft Liner: Inner and outer stainless steel liners with acoustic pads between them	J79 and F404	unknown	--	--	--	--	--	--	Test cell 20 currently undergoing modernization

[a] Cross section is elliptical.

[b] Each hush house.

[c] Augmenter is followed by 20-ft muffler.

[d] Augmenter expands to 7-ft-diam muffler section.

[e] Front section of augmenter is curved.

[f] Sections from 1 ft 11 in. diameter to 3 ft 4 in. diameter.

[g] Telescoping sections.

[h] Sections from 5 ft 10 in. to 10 ft 2 in. inner diameter.

[i] Slightly tapered.

Appendix D

COMPUTER MODELLING OF AUGMENTER TUBE

The relationships in Appendixes A and B were programmed in FORTRAN IV. Figure D-1 is a flow chart of the program. A listing and some typical results follow.

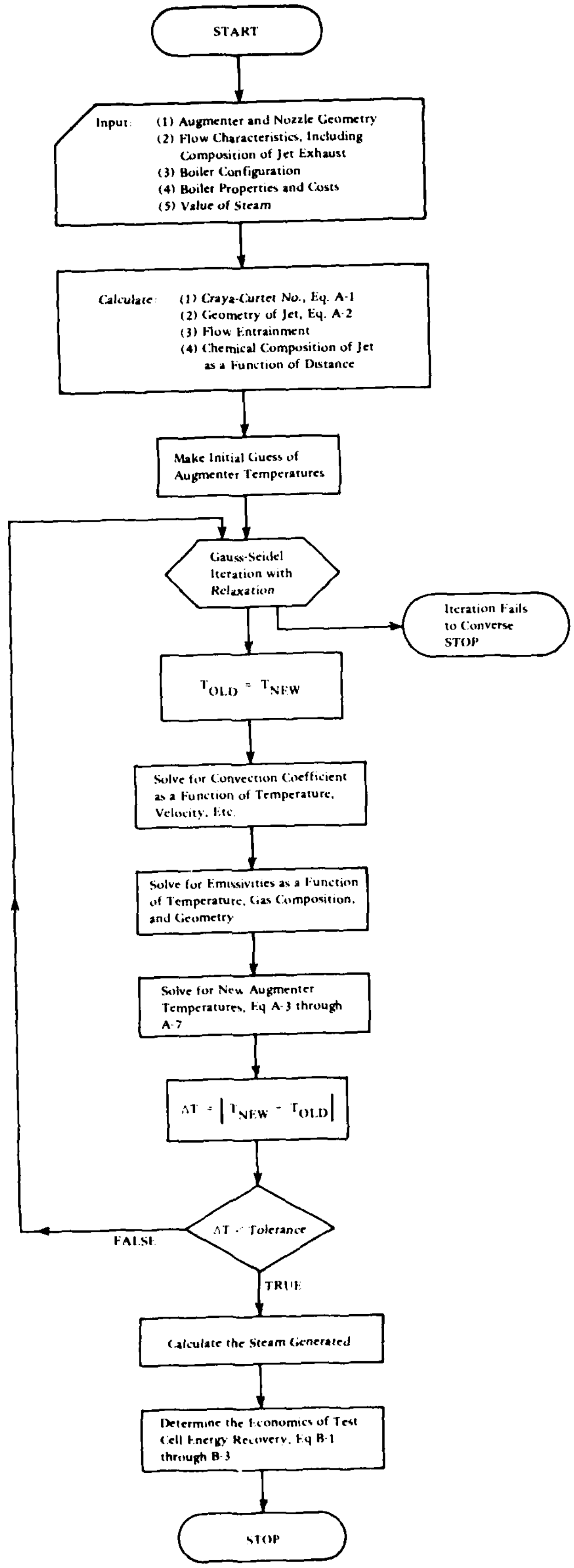

Figure D-1. Flowchart of computer modeling of augmenter tube.

PROGRAM LISTING

```
      PROGRAM JETEST (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C  PROGRAM TO CALCULATE THE HEAT TRANSFER FROM A JET EXHAUST TO THE
C  TEST CELL AUGMENTER WALLS OR TO BOILERS WRAPPED AROUND THE WALLS
C  OR TO BOILERS PLACED IN THE JET STREAM AT THE AUGMENTER EXIT OR BOTH
C
C  STEADY STATE AXISYMMETRIC FLOW THRU A CYLINDRICAL DUCT IS ASSUMED
C  IN ADDITION, IT IS ASSUMED THAT BOTH THE JET AND SECONDARY FLOW ARE
C  TURBULENT, PERFECTLY MIXED IDEAL GASES
C
      REAL MJET(51),MSEC(51),KDUCT,KAINT,KAEXT,KPAD,N2(50),L(50),KAIR,
     1MUAIR,MSTM1(50),K
      INTEGER TYPE
      COMMON O2,N2,CO2,H2O,CO,H2,LUM
      DIMENSION T(50,4),TEMP(50,4),HCONV(50),ARAD(50),F(50,50),DELM(50)
     1,O2(50),AJET(50),RJET(50),RADST(50),ABOIL(2),TSTM(2),PSTM(2)
     2,HSTM(2),RADIN(50),RADOUT(50),Z(50),CO2(50),H2O(50),CO(50),H2(50)
     3,QCONV(50),EMIS(50),F1(50,50),UJET(51)
      DIMENSION PV(25),SIR(25),P1B(50),P4B(50),P5B(50)
      DATA PI,PRESS,RAIR,SIGMA,TDATUM/3.1416,2116.,53.36,0.1714E-8,520./
      DATA ITER,TOL/100,1./
      DATA R/-0.5/
      DATA EMPIR1,EMPIR2/14.,14./
C
C  INPUT THE NUMBER OF AXIAL SEGMENTS THAT THE AUGMENTER TUBE WILL BE
C  DIVIDED INTO, N.LE.50
      READ(5,1) N
C  INPUT THE AUGMENTER GEOMETRY....THE AREA OF THE JET NOZZLE AND THE
C  AREA OF THE AUGMENTER INLET, BOTH IN SQFT....THE LENGTH OF THE
C  AUGMENTER IN FEET....AND THE THICKNESSES OF THE DUCT AND THE ACOUSTIC
C  PILLOWS IN INCHES
      READ(5,2) AJET(1),AAUG,AUGL,DELR,DELPAD
C  INPUT SECONDARY FLOW RATE IN LBS/SEC AND ITS TEMPERATURE IN DEGF
      READ(5,3) MSEC(1),T(1,2)
C  INPUT JET FLOW RATE IN LBS/SEC, TOTAL TEMPERATURE AND TOTAL PRESSURE
C  OF JET IN DEGF AND PSIA, AND RATIO OF JET SPECIFIC HEATS
      READ(5,4) MJET(1),TTJET,PTJET,GAMMA
C  INPUT THE CHEMICAL COMPOSITION OF THE JET....PERCENT WEIGHT OF
C  OXYGEN, NITROGEN, CARBON DIOXIDE, CARBON MONOXIDE, WATER VAPOR, AND
C  HYDROGEN
      READ(5,6) O2(1),N2(1),CO2(1),CO(1),H2O(1),H2(1)
C  INPUT THE LENGTH OF THE LUMINOUS PORTION OF THE JET EXHAUST IN FEET
      READ(5,3) FLAME
C  INPUT THE COEFFICIENT OF THERMAL CONDUCTIVITY OF THE DUCT WALLS AND
C  THE ACOUSTIC PILLOWS IN BTU/HR-FT-DEGF....IF THE PILLOWS ARE NOT
C  USED, INPUT DELPAD=0. AND KPAD=10000.
      READ(5,7) KDUCT,KPAD
C  INPUT BOUNDARY CONDITIONS TO SIMULATE THE HOUSE STRUCTURE ACTING AS
C  A HEAT SINK.....THE EFFECTIVE TEMPS AND THERMAL CONDUCTANCES, IN DEGF
C  AND BTU/HR-DEGF, AT THE AUGMENTER INLET AND EXIT, IN THAT ORDER
      READ(5,4) TINT,KAINT,TEXT,KAEXT
C  INPUT AMBIENT CONDITIONS....THE TEMP IN DEGF AND THE NATURAL
C  CONVECTION HEAT TRANSFER COEFFICIENT IN BTU/HR-SQFT-DEGF
      READ(5,3) TAMB,HAMB
C  INPUT THE HEAT EXCHANGER (BOILER) CONFIGURATION
C      "1" SIGNIFIES NO HEAT EXCHANGERS
C      "2" SIGNIFIES WATERWALLS WRAPPED AROUND THE AUGMENTER TUBES
C      "3" SIGNIFIES CONVECTION BOILER IN THE AUGMENTER GASES AT EXIT
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C       "4" SIGNIFIES BOTH WATERWALLS AND CONVECTION BOILERS
        READ(5,1) TYPE
        IF (TYPE.EQ.1) GO TO 10
C   INPUT THE APPLICABLE BOILER CHARACTERISTICS
C   INPUT THE TOTAL NUMBER OF HRS PER DAY THAT THE TEST CELL IS UTILIZED
C   WITH THIS ENGINE AND AT THIS POWER SETTING AND ALSO INPUT IND2.GE.7,
C   FOR A PARAMETRIC STUDY INPUT TIME=0.25 AND IND2=0....INPUT PURCHASE
C   PRICE OF THE WATER-WALL AND CONVECTION HEAT RECOVERY HEAT EXCHANGERS
C   IN THAT ORDER....IF THERE IS ONLY ONE, INPUT ZERO IN THE SPACE
C   FOR THE OTHER
        READ(5,78) TIME,IND2,PRICE1,PRICE2
C   INPUT THE CURRENT COST OF THE STEAM IN $/MBTU, THE DISCOUNT RATE, AND
C   THE LONG TERM ESCALATION RATE OF THE COST OF STEAM IN PERCENT
C   PER YEAR
        READ(5,4) COST,DISC,ESC
        IF (TYPE.EQ.3) GO TO 5
C   INPUT THE WATERWALL CHARACTERISTICS....STEAM TEMP IN DEGF, STEAM
C   PRESSURE IN PSIA, HEAT OF VAPORIZATION IN BTU/LB, AND THE TOTAL HEAT
C   TRANSFER AREA IN SQFT
        READ(5,4) TSTM(1),PSTM(1),HSTM(1),ABOIL(1)
        TSTM(1)=TSTM(1)+460.
C   INPUT THE LOCATION OF THE WATER-WALLS....FRONT AND BACK IN TERMS OF
C   FEET FROM THE AUGMENTER INLET
        READ(5,3) FRONT,BACK
        IF (TYPE.EQ.2) GO TO 10
C   IF BOTH BOILERS ARE UTILIZED, INPUT WATERWALL CHARACTERISTICS FIRST
C   INPUT THE CONVECTION BOILER CHARACTERISTICS....STEAM TEMP, PRESSURE,
C   AND HEAT OF VAPORIZATION, TOTAL HEAT TRANSFER AREA, AND THE OUTER
C   DIAMETER OF THE TUBES IN INCHES
      5 READ(5,8) TSTM(2),PSTM(2),HSTM(2),ABOIL(2),DTUBE
        TSTM(2)=TSTM(2)+460.
C
C   PRINT ALL DIMENSIONS, PROPERTIES, AND BOUNDARY CONDITIONS
     10 WRITE(6,11)
        WRITE(6,12) AJET(1),AAUG,AUGL,DELR,DELPAD
        WRITE(6,13)
        WRITE(6,14) MJET(1),TTJET,PTJET,GAMMA
        WRITE(6,16)
        WRITE(6,17) O2(1),N2(1),CO2(1),CO(1),H2O(1),H2(1),FLAME
        WRITE(6,18)
        WRITE(6,19) MSEC(1),T(1,2)
        WRITE(6,67)
        WRITE(6,68) TAMB,HAMB
        WRITE(6,21)
        WRITE(6,22) KDUCT
        IF (DELPAD.LE.0.) GO TO 15
        WRITE(6,23) KPAD
     15 WRITE(6,24)
        WRITE(6,26) TINT,KAINT,TEXT,KAEXT
        IF (TYPE.EQ.1) WRITE(6,27)
C
C   SIMPLIFYING AND PRELIMINARY CALCULATIONS
        DELR=DELR/12.
        DELPAD=DELPAD/12.
        DTUBE=DTUBE/12.
        DELZ=AUGL/(N-1)
        LUM=INT(FLAME/DELZ)
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```
      RAUG=SQRT(AAUG/PI)
      RJET(1)=SQRT(AJET(1)/PI)
      AREAR=2.*PI*RAUG*DELZ
      AREAZ=PI*((RAUG+DELR)**2-RAUG**2)
      K=(DELR+DELPAD)/(DELR/KDUCT+DELPAD/KPAD)
      PTJET=PTJET*144.
      T(1,2)=T(1,2)+460.
      TTJET=TTJET+460.
      TINT=TINT+460.
      TEXT=TEXT+460.
      TAMB=TAMB+460.
      RATIO=(1.+ESC/100.)/(1.+DISC/100.)
      P1=K*AREAR/2./(DELR+DELPAD)
      P2=AREAR/2.
      P3=KDUCT*AREAZ/DELZ
      P4=K/(DELR+DELPAD)
      P5=2.*P1
      P6=KDUCT/DELZ
      P7=SIGMA*AREAR
      IF ((TYPE.EQ.1).OR.(TYPE.EQ.3)) GO TO 20
      IFRONT=INT(FRONT/DELZ)+1
      IBACK=INT(BACK/DELZ)+1
      IF (IBACK.GT.N) IBACK=N
C
C  CALCULATE BULK VELOCITIES AT AUGMENTER INLET
   20 RHOS=PRESS/RAIR/T(1,2)
      VSEC=MSEC(1)/RHOS/(AAUG-AJET(1))
      POWER=(GAMMA-1.)/GAMMA
      T(1,1)=TTJET*(PRESS/PTJET)**POWER
      RHOJ=PRESS/RAIR/T(1,1)
      VJET=MJET(1)/RHOJ/AJET(1)
      UJET(1)=VJET
      UJET(2)=UJET(1)
C  CALCULATE THE CRAYA-CURTET NUMBER
      A=AJET(1)/AAUG
      B=1.-A
      C=0.5-A
      CRAYA=(A*VJET+B*VSEC)/(A*VJET**2+C*VSEC**2-0.5*(A*VJET+B*VSEC)**2)
     1**0.5
      WRITE(6,34) VJET,VSEC,CRAYA
C
C  CALCULATE THE EXPANSION OF THE JET USING THE EMPIRICAL RELATIONSHIPS
C  OF BECKER, ET AL, 9TH SYMP.(INT) ON COMB.,1963
C  THE CONSTANTS HAVE BEEN ADJUSTED TO FIT TEST CELL DATA
      FACTOR=0.
      IF (CRAYA.GT.0.7) GO TO 40
      XR=4.07*EXP(3.54*CRAYA)
      FACTOR=1./XR**1.667
      A=SQRT(A)
      X=AUGL/RAUG
      DEV=X
      DO 30 I=1,ITER
      DSAVE=DEV
      XSAVE=X
      FF=0.131*(FACTOR*X**2.667+X)-1.+A
      DFFDX=0.348*FACTOR*X**1.667+0.131
      X=X-FF/DFFDX
```

```
      DEV=ABS(X-XSAVE)
      IF (DEV.LE.DSAVE) GO TO 25
      WRITE(6,36)
      WRITE(6,37)
      WRITE(6,38)
      GO TO 500
   25 CONTINUE
      IF (DEV.LE.TOL) GO TO 35
   30 CONTINUE
      WRITE(6,36)
      WRITE(6,39) TOL,ITER
      WRITE(6,38)
   35 XSEP=X*RAUG
      GO TO 45
   40 XSEP=7.91*(RAUG-RJET(1))
   45 CONTINUE
C  DETERMINE IF JET EVER REACHES AUGMENTER WALL
      IF (XSEP.GT.AUGL) GO TO 50
      NSEP=INT(XSEP/DELZ)+2
      IF (NSEP.GT.N) NSEP=N
      WRITE(6,41) XSEP
      GO TO 55
   50 NSEP=10000
      WRITE(6,42)
   55 CONTINUE
C
C  CALCULATE THE PROGRESSIVE RADII OF THE JET EXHAUST....AGAIN USE THE
C  EMPIRICAL RELATIONSHIPS OF BECKER...
      Z(1)=0.
      DELM(1)=0.
      DO 60 I=2,N
      Z(I)=(I-1)*DELZ
      RJET(I)=RJET(1)+0.131*Z(I)*(1.+FACTOR*(Z(I)/RAUG)**1.667)
      IF (CRAYA.GT.0.7) RJET(I)=RJET(1)+0.1265*Z(I)
      IF (RJET(I).GT.RAUG) RJET(I)=RAUG
C  CALCULATE SECONDARY FLOW ENTRAINED BY THE EXPANDING JET
      DELM(I)=RHOS*VSEC*PI*(RJET(I)**2-RJET(I-1)**2)
   60 CONTINUE
      KK=N-1
      DO 490 I=1,KK
      MJET(I+1)=MJET(I)+DELM(I)
      MSEC(I+1)=MSEC(I)-DELM(I+1)
  490 CONTINUE
      MJET(N+1)=MJET(N)
      WRITE(6,9)
      II=1
      DO 65 I=1,5
      LIM=10*I
      IPRINT=MIN0(LIM,N)
      WRITE(6,43)
      WRITE(6,44) (Z(J),J=II,IPRINT)
      WRITE(6,45) (RJET(J),J=II,IPRINT)
      WRITE(6,47) (MJET(J+1),J=II,IPRINT)
      WRITE(6,48) (MSEC(J),J=II,IPRINT)
      IF (IPRINT.GE.N) GO TO 70
      II=IPRINT+1
   65 CONTINUE
```

```
   70 CONTINUE
C
C  CALCULATE RADIATION CONSTANTS....AREAS, MEAN BEAM LENGTHS, AND
C  SHAPE FACTORS
      DO 75 I=1,N
      ARAD(I)=2.*PI*RJET(I)*DELZ
      L(I)=1.9*RJET(I)
   75 CONTINUE
      ARAD(1)=ARAD(1)/2.
      ARAD(N)=ARAD(N)/2.
      CALL SHAPE(RJET,RAUG,DELZ,F,N)
      CALL SHAPE1(RAUG,DELZ,F1,N)
C
C  CALCULATE THE COMPOSITION OF THE JET EXHAUST IN MOLES/LB OF EXHAUST
      O2(1)=O2(1)/3200.
      N2(1)=N2(1)/2800.
      CO2(1)=CO2(1)/4400.
      H2O(1)=H2O(1)/1800.
      CO(1)=CO(1)/2800.
      H2(1)=H2(1)/200.
      DO 80 I=2,N
      O2(I)=O2(I-1)+0.0072*DELM(I)/MJET(I)
      N2(I)=N2(I-1)+0.0272*DELM(I)/MJET(I)
      CO2(I)=CO2(I-1)*MJET(I-1)/MJET(I)
      H2O(I)=H2O(I-1)*MJET(I-1)/MJET(I)
      CO(I)=CO(I-1)*MJET(I-1)/MJET(I)
      H2(I)=H2(I-1)*MJET(I-1)/MJET(I)
   80 CONTINUE
C
C  USE GAUSS-SEIDEL ITERATION, WITH RELAXATION, TO SIMULTANEOUSLY SOLVE
C  FOR JET AND SECONDARY FLOW TEMPERATURES AS WELL AS TEMPERATURES ON
C  THE INSIDE AND OUTSIDE OF THE AUGMENTER WALL
C
C  FIRST, INITIALIZE TEMPS FOR THE ITERATION
      TGUESS=(MJET(1)*T(1,1)+MSEC(1)*T(1,2))/(MJET(1)+MSEC(1))
      T(1,3)=TGUESS
      T(1,4)=TAMB
      DO 85 I=2,N
      T(I,1)=T(1,1)-(T(1,1)-TGUESS)*Z(I)/AUGL
      T(I,2)=T(1,2)
      T(I,3)=TGUESS
      T(I,4)=TAMB
   85 CONTINUE
C  AND MAKE SOME ADDITIONAL PREPATORY CALCULATIONS
      DO 86 I=1,N
      MJET(I)=3600.*MJET(I)
      MSEC(I)=3600.*MSEC(I)
      DELM(I)=3600.*DELM(I)
      P1B(I)=P1
      P4B(I)=P4
      P5B(I)=P5
      IF ((TYPE.EQ.1).OR.(TYPE.EQ.3)) GO TO 86
      IF ((I.LT.IFRONT).OR.(I.GT.IBACK)) GO TO 86
      P1B(I)=KDUCT*AREAR/2./DELR
      P4B(I)=KDUCT/DELR
      P5B(I)=2.*P1B(I)
   86 CONTINUE
```

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      MJET(N+1)=MJET(N)
      MSEC(N+1)=MSEC(N)
      IND1=MIN0(N,NSEP)
      IND3=MIN0(N-1,NSEP-1)
      JK=NSEP-1
      DEVMAX=T(1,1)
C
C  BEGIN THE ITERATION
      DO 400 I=1,ITER
      DSAVE=DEVMAX
      DEVMAX=0.
C
C  CALCULATE THE CONVECTIVE HEAT TRANSFER FILM COEFFICIENTS
C  USE THE RELATIONSHIPS OF MCADAMS FOR TURBULENT FLOW THRU A DUCT,
C  HOWEVER, USE BOTH VELOCITIES AND THE EQUIVELENT DIAMETER OF THE
C  SECONDARY FLOW "DUCT" TO CALCULATE REYNOLDS NO....THE CONSTANT IS
C  EMPIRICALLY ADJUSTED TO FIT TEST CELL TEMP DATA
      DO 90 II=1,IND3
      FACTOR=T(II,2)**1.5/(225.+T(II,2))
      KAIR=9.26E-4*FACTOR
      MUAIR=2.694E-3*FACTOR
      RHOAIR=PRESS/RAIR/T(II,2)
      VCONV1=VSEC*T(II,2)/T(1,2)
      RHOJ=PRESS/RAIR/T(II,1)
      VCONV2=MJET(II)/RHOJ/PI/RJET(II)**2/3600.
      VCONV=A*VCONV2+B*VCONV1
      DEQV=2.*(RAUG-RJET(II))
      HCONV(II)=EMPIR1*KAIR/DEQV**0.2*(VCONV*RHOAIR/MUAIR)**0.8
      HCONV(II)=HCONV(II)/II
   90 CONTINUE
      IF (NSEP.GT.N) GO TO 100
C  ONCE THE JET REACHES THE WALL, THE PROBLEM SIMPLY BECOMES THAT
C  OF TURBULENT FLOW THRU A CIRCULAR DUCT
      DO 95 II=IND1,N
      FACTOR=T(II,1)**1.5/(225.+T(II,1))
      KAIR=9.26E-4*FACTOR
      MUAIR=2.694E-3*FACTOR
      RHOAIR=PRESS/RAIR/T(II,1)
      VCONV=(MSEC(1)+MJET(1))/AAUG/RHOAIR/3600.
      HCONV(II)=EMPIR2*KAIR*(VCONV*RHOAIR/MUAIR)**0.8/RAUG**0.2
   95 CONTINUE
  100 CONTINUE
C
C  CALCULATE BULK VELOCITIES OF THE JET
      DO 102 II=2,N
      RHOJ=PRESS/RAIR/T(II,1)
      AJET(II)=PI*RJET(II)**2
      VJET(II+1)=MJET(II+1)/RHOJ/AJET(II)/3600.
  102 CONTINUE
C
      SAVE=T(1,3)
      RADIN(1)=0.
      DO 105 II=1,N
      EMSS=EMISS(T(II,1),L(II),II)
      ALFA=EMSS*SQRT(T(II,1)/T(1,3))
C  RADIATION REACHING THE AUGMENTER WALLS HAS TWO SOURCES...FROM THE
C  EXHAUST GAS OR FROM OTHER PARTS OF THE WALL
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C  NEGLECT THE FACT THAT SOME RADIATION BETWEEN WALL SEGMENTS DOES NOT
C  PASS THROUGH THE JET
      RADIN(1)=RADIN(1)+SIGMA*ARAD(II)*F(II,1)*(EMSS*T(II,1)**4-ALFA
     1*T(1,3)**4)+P7*F1(II,1)*(1.-EMSS)*(T(II,3)**4-T(1,3)**4)
  105 CONTINUE
      T(1,3)=(P1B(1)*T(1,4)+P2*HCONV(1)*T(1,2)+KAINT*TINT+P3*T(2,3)
     1+RADIN(1))/(P1B(1)+P2*HCONV(1)+P3+KAINT)
      T(1,3)=T(1,3)+R*(T(1,3)-SAVE)
      DEV=ABS(T(1,3)-SAVE)
      IF (DEV-DEVMAX) 115,115,110
  110 DEVMAX=DEV
  115 CONTINUE
      DO 125 J=1,N
      SAVE=T(J,4)
      IF ((TYPE.EQ.2).OR.(TYPE.EQ.4)) GO TO 116
      T(J,4)=(HAMB*TAMB+P4*T(J,3))/(HAMB+P4)
      GO TO 117
  116 IF ((J.GE.IFRONT).AND.(J.LE.IBACK)) T(J,4)=(1000.*TSTM(1)+P6*
     1T(J,3))/(1000.+P6)
  117 T(J,4)=T(J,4)+R*(T(J,4)-SAVE)
      DEV=ABS(T(J,4)-SAVE)
      IF (DEV-DEVMAX) 125,125,120
  120 DEVMAX=DEV
  125 CONTINUE
      DO 140 J=2,IND3
      SAVE=T(J,1)
      RADOUT(J)=0.
      EMSS=EMISS(T(J,1),L(J),J)
      DO 130 II=1,N
      ALFA=EMSS*SQRT(T(J,1)/T(II,3))
C  IT IS ASSUMED THAT THERE IS NO RADIATION BETWEEN DIFFERENT LOCATIONS
C  ALONG THE JET EXHAUST STREAM
      RADOUT(J)=RADOUT(J)+SIGMA*ARAD(J)*F(J,II)*(EMSS*T(J,1)**4-ALFA
     1*T(II,3)**4)
  130 CONTINUE
      CPIN=SPHT(T(J-1,1),J-1)
      CPOUT=SPHT(T(J,1),J)
      T(J,1)=(MJET(J+1)*CPOUT*TDATUM+MJET(J)*CPIN*(T(J-1,1)-TDATUM)+
     10.24*DELM(J)*(T(J-1,2)-TDATUM)-RADOUT(J)+2.E-5*(MJET(J)*
     2UJET(J)**2-MJET(J+1)*UJET(J+1)**2))/MJET(J+1)/CPOUT
      T(J,1)=T(J,1)+R*(T(J,1)-SAVE)
      DEV=ABS(T(J,1)-SAVE)
      IF (DEV-DEVMAX) 140,140,135
  135 DEVMAX=DEV
  140 CONTINUE
      DO 150 J=2,IND3
      SAVE=T(J,2)
      T(J,2)=(0.24*((DELM(J+1)+MSEC(J+1))*TDATUM+MSEC(J)*(T(J-1,2)
     1-TDATUM))+AREAR*HCONV(J)*T(J,3))/(0.24*(DELM(J+1)+MSEC(J+1))
     2+AREAR*HCONV(J))
      T(J,2)=T(J,2)+R*(T(J,2)-SAVE)
      DEV=ABS(T(J,2)-SAVE)
      IF (DEV-DEVMAX) 150,150,145
  145 DEVMAX=DEV
  150 CONTINUE
      DO 165 J=2,IND3
      SAVE=T(J,3)
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      RADIN(J)=0.
      DO 155 II=1,N
      EMSS=EMISS(T(II,1),L(II),II)
      ALFA=EMSS*SQRT(T(II,1)/T(J,3))
      RADIN(J)=RADIN(J)+SIGMA*ARAD(II)*F(II,J)*(EMSS*T(II,1)**4-ALFA
     1*T(J,3)**4)+P7*F1(II,J)*(1.-EMSS)*(T(II,3)**4-T(J,3)**4)
  155 CONTINUE
      T(J,3)=(P5B(J)*T(J,4)+P3*(T(J+1,3)+T(J-1,3))+AREAR*HCONV(J)*T(J,2)
     1+RADIN(J))/(P5B(J)+2.*P3+AREAR*HCONV(J))
      T(J,3)=T(J,3)+R*(T(J,3)-SAVE)
      DEV=ABS(T(J,3)-SAVE)
      IF (DEV-DEVMAX) 165,165,160
  160 DEVMAX=DEV
  165 CONTINUE
C  THE DOWNSTREAM CALCULATIONS DEPEND UPON WHETHER THE JET EVER REACHES
C  AUGMENTER WALL
      IF (NSEP-N) 170,230,260
C  THE CASE WHERE THE JET REACHES THE WALL UPSTREAM FROM AUGMENTER EXIT
  170 DO 185 J=NSEP,KK
      RADOUT(J)=SIGMA*ARAD(J)*EMISS(T(J,1),L(J),J)*(T(J,1)**4
     1-SQRT(T(J,1)/T(J,3))*T(J,3)**4)
      CPIN=SPHT(T(J-1,1),J-1)
      CPOUT=SPHT(T(J,1),J)
      SAVE=T(J,1)
      T(J,1)=(MJET(J+1)*CPOUT*TDATUM+AREAR*HCONV(J)*T(J,3)+MJET(J)
     1*CPIN*(T(J-1,1)-TDATUM)+0.24*DELM(J)*(T(J-1,2)-TDATUM)-RADOUT(J)
     2+2.E-5*(MJET(J)*UJET(J)**2-MJET(J+1)*UJET(J+1)**2))/(MJET(J+1)*
     3CPOUT+AREAR*HCONV(J))
      T(J,1)=T(J,1)+R*(T(J,1)-SAVE)
      DEV=ABS(T(J,1)-SAVE)
      IF (DEV-DEVMAX) 185,185,180
  180 DEVMAX=DEV
  185 CONTINUE
      DO 200 J=NSEP,KK
      RADIN(J)=0.
      DO 190 II=1,N
      EMSS=EMISS(T(II,1),L(II),II)
      ALFA=EMSS*SQRT(T(II,1)/T(J,3))
      RADIN(J)=RADIN(J)+SIGMA*ARAD(II)*F(II,J)*(EMSS*T(II,1)**4
     1-ALFA*T(J,3)**4)+P7*F1(II,J)*(1.-EMSS)*(T(II,3)**4-T(J,3)**4)
  190 CONTINUE
      SAVE=T(J,3)
      T(J,3)=(P5B(J)*T(J,4)+P3*(T(J+1,3)+T(J-1,3))+AREAR*HCONV(J)*T(J,1)
     1+RADIN(J))/(P5B(J)+2.*P3+AREAR*HCONV(J))
      T(J,3)=T(J,3)+R*(T(J,3)-SAVE)
      DEV=ABS(T(J,3)-SAVE)
      IF (DEV-DEVMAX) 200,200,195
  195 DEVMAX=DEV
  200 CONTINUE
      SAVE=T(N,3)
      RADIN(N)=0.
      DO 205 II=1,N
      EMSS=EMISS(T(II,1),L(II),II)
      ALFA=EMSS*SQRT(T(II,1)/T(N,3))
      RADIN(N)=RADIN(N)+SIGMA*ARAD(II)*F(II,N)*(EMSS*T(II,1)**4-ALFA
     1*T(N,3)**4)+P7*F1(II,N)*(1.-EMSS)*(T(II,3)**4-T(N,3)**4)
  205 CONTINUE
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      T(N,3)=(P1B(N)*T(N,4)+P3*T(N-1,3)+KAEXT*TEXT+P2*HCONV(N)*T(N,1)
     1+RADIN(N))/(P1B(N)+P3+KAEXT+P2*HCONV(N))
      T(N,3)=T(N,3)+R*(T(N,3)-SAVE)
      DEV=ABS(T(N,3)-SAVE)
      IF (DEV-DEVMAX) 215,215,210
  210 DEVMAX=DEV
  215 CONTINUE
      SAVE=T(N,1)
      CPOUT=SPHT(T(N,1),N)
      CPIN=SPHT(T(N-1,1),N-1)
      EMSS=EMISS(T(N,1),L(N),N)
      RADOUT(N)=SIGMA*ARAD(N)*EMSS*(T(N,1)**4-SQRT(T(N,1)/T(N,3))
     1*T(N,3)**4)
      T(N,1)=(MJET(N+1)*CPOUT*TDATUM-RADOUT(N)+MJET(N)*CPIN*(T(N-1,1)
     1-TDATUM)+P2*HCONV(N)*T(N,3)+2.E-5*(MJET(N)*UJET(N)**2-MJET(N+1)
     2*UJET(N+1)**2))/(MJET(N+1)*CPOUT+P2*HCONV(N))
      T(N,1)=T(N,1)+R*(T(N,1)-SAVE)
      DEV=ABS(T(N,1)-SAVE)
      IF (DEV-DEVMAX) 225,225,220
  220 DEVMAX=DEV
  225 CONTINUE
      DO 226 J=NSEP,N
      T(J,2)=T(J,1)
  226 CONTINUE
      GO TO 305
C  THE CASE WHERE THE JET REACHES THE WALL AT THE AUGMENTER EXIT
  230 SAVE=T(N,3)
      RADIN(N)=0.
      DO 235 II=1,N
      EMSS=EMISS(T(II,1),L(II),II)
      ALFA=EMSS*SQRT(T(II,1)/T(N,3))
      RADIN(N)=RADIN(N)+SIGMA*ARAD(II)*F(II,N)*(EMSS*T(II,1)**4-ALFA
     1*T(N,3)**4)+P7*F1(II,N)*(1.-EMSS)*(T(II,3)**4-T(N,3)**4)
  235 CONTINUE
      T(N,3)=(P1B(N)*T(N,4)+P3*T(N-1,3)+KAEXT*TEXT+P2*HCONV(N)*T(N,1)
     1+RADIN(N))/(P1B(N)+P3+KAEXT+P2*HCONV(N))
      T(N,3)=T(N,3)+R*(T(N,3)-SAVE)
      DEV=ABS(T(N,3)-SAVE)
      IF (DEV-DEVMAX) 245,245,240
  240 DEVMAX=DEV
  245 CONTINUE
      SAVE=T(N,1)
      CPOUT=SPHT(T(N,1),N)
      CPIN=SPHT(T(N-1,1),N-1)
      EMSS=EMISS(T(N,1),L(N),N)
      RADOUT(N)=SIGMA*ARAD(N)*EMSS*(T(N,1)**4-SQRT(T(N,1)/T(N,3))
     1*T(N,3)**4)
      T(N,1)=(MJET(N+1)*CPOUT*TDATUM+MJET(N)*CPIN*(T(N-1,1)-TDATUM)+P2
     1*HCONV(N)*T(N,3)+0.24*DELM(N)*(T(N-1,2)-TDATUM)-RADOUT(N)
     2+2.E-5*(MJET(N)*UJET(N)**2-MJET(N+1)*UJET(N+1)**2))/(MJET(N+1)
     3*CPOUT+P2*HCONV(N))
      T(N,1)=T(N,1)+R*(T(N,1)-SAVE)
      DEV=ABS(T(N,1)-SAVE)
      IF (DEV-DEVMAX) 255,255,250
  250 DEVMAX=DEV
  255 CONTINUE
      T(N,2)=T(N,1)
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```
      GO TO 305
C  THE CASE WHERE THE JET NEVER REACHES THE AUGMENTER WALL
  260 SAVE=T(N,3)
      RADIN(N)=0.
      DO 265 II=1,N
      EMSS=EMISS(T(II,1),L(II),II)
      ALFA=EMSS*SQRT(T(II,1)/T(N,3))
      RADIN(N)=RADIN(N)+SIGMA*ARAD(II)*F(II,N)*(EMSS*T(II,1)**4-ALFA
     1*T(N,3)**4)+P7*F1(II,N)*(1.-EMSS)*(T(II,3)**4-T(N,3)**4)
  265 CONTINUE
      T(N,3)=(P1B(N)*T(N,4)+P3*T(N-1,3)+KAEXT*TEXT+P2*HCONV(N)*T(N,2)
     1+RADIN(N))/(P1B(N)+P3+KAEXT+P2*HCONV(N))
      T(N,3)=T(N,3)+R*(T(N,3)-SAVE)
      DEV=ABS(T(N,3)-SAVE)
      IF (DEV-DEVMAX) 275,275,270
  270 DEVMAX=DEV
  275 CONTINUE
      SAVE=T(N,1)
      RADOUT(N)=0.
      EMSS=EMISS(T(N,1),L(N),N)
      DO 280 II=1,N
      ALFA=EMSS*SQRT(T(N,1)/T(II,3))
      RADOUT(N)=RADOUT(N)+SIGMA*ARAD(N)*F(N,II)*(EMSS*T(N,1)**4-ALFA
     1*T(II,3)**4)
  280 CONTINUE
      CPIN=SPHT(T(N-1,1),N-1)
      CPOUT=SPHT(T(N,1),N)
      T(N,1)=(MJET(N+1)*CPOUT*TDATUM+MJET(N)*CPIN*(T(I-1,1)-TDATUM)+
     10.24*DELM(N)*(T(N-1,2)-TDATUM)-RADOUT(N)+2.E-5*(MJET(N)*
     2UJET(N)**2-MJET(N+1)*UJET(N+1)**2))/MJET(N+1)/CPOUT
      T(N,1)=T(N,1)+R*(T(N,1)-SAVE)
      DEV=ABS(T(N,1)-SAVE)
      IF (DEV-DEVMAX) 290,290,285
  285 DEVMAX=DEV
  290 CONTINUE
      SAVE=T(N,2)
      T(N,2)=(0.24*MSEC(N+1)*TDATUM+MSEC(N)*(T(N-1,2)-TDATUM)+P2
     1*HCONV(N)*T(N,3))/(0.24*MSEC(N+1)+P2*HCONV(N))
      T(N,2)=T(N,2)+R*(T(N,2)-SAVE)
      DEV=ABS(T(N,2)-SAVE)
      IF (DEV-DEVMAX) 300,300,295
  295 DEVMAX=DEV
  300 CONTINUE
  305 CONTINUE
C
C  CHECK TO SEE IF ITERATION IS CONVERGING
      IF (DEVMAX.LE.DSAVE) GO TO 310
      WRITE(6,36)
      WRITE(6,49)
      WRITE(6,38)
      GO TO 500
C  CHECK TO SEE IF ITERATION HAS CONVERGED TO WITHIN TOLERANCE
  310 IF (DEVMAX.LE.TOL) GO TO 405
C
  400 CONTINUE
C
      WRITE(6,36)
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      WRITE(6,51) TOL,ITER
      WRITE(6,38)
  405 CONTINUE
      WRITE(6,39) I,DEVMAX
C  CONVERT TEMPS FROM RANKINE TO FAHRENHEIT AND PRINT RESULTS
      DO 410 M=1,N
      DO 410 J=1,4
      TEMP(M,J)=T(M,J)-460.
  410 CONTINUE
      II=1
      ISEC=0
      DO 415 M=1,5
      LIM=10*M
      IPRINT=MIN0(LIM,N)
      IPRNT=MIN0(LIM,NSEP-1)
      WRITE(6,52)
      WRITE(6,44) (Z(J),J=II,IPRINT)
      WRITE(6,53) (TEMP(J,1),J=II,IPRINT)
      IF (ISEC.GT.0) GO TO 412
      WRITE(6,54) (TEMP(J,2),J=II,IPRNT)
  412 WRITE(6,56) (TEMP(J,3),J=II,IPRINT)
      WRITE(6,57) (TEMP(J,4),J=II,IPRINT)
      IF (IPRINT.GE.N) GO TO 420
      II=IPRINT+1
      IF (IPRNT.GE.JK) ISEC=1
  415 CONTINUE
  420 CONTINUE
C  PRINT JET VELOCITY AT AUGMENTER EXIT
      WRITE(6,69) UJET(N)
C  PRINT THE HEAT TRANSFER CHARACTERISTICS OF THE JET EXHAUST
      DO 421 M=1,N
      EMIS(M)=EMISS(T(M,1),L(M),M)
  421 CONTINUE
      II=1
      DO 422 M=1,5
      LIM=10*M
      IPRINT=MIN0(LIM,N)
      WRITE(6,72)
      WRITE(6,44) (Z(J),J=II,IPRINT)
      WRITE(6,73) (HCONV(J),J=II,IPRINT)
      WRITE(6,74) (EMIS(J),J=II,IPRINT)
      IF (IPRINT.GE.N) GO TO 423
      II=IPRINT+1
  422 CONTINUE
  423 CONTINUE
C
C  CALCULATE THE STEAM GENERATION....ASSUME FEED WATER ENTERS THE BOILER
C  IN A SATURATED CONDITION
      IF (TYPE.EQ.1) GO TO 500
      IF (TYPE.EQ.2) WRITE(6,28)
      IF (TYPE.EQ.3) WRITE(6,29)
      IF (TYPE.EQ.4) WRITE(6,31)
      IF (TYPE.EQ.3) GO TO 455
C  STEAM GENERATION IN WATER WALL BOILER
      DO 424 I=1,N
      QCONV(I)=0.
      MSTM1(I)=0.
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      RADST(I)=0.
  424 CONTINUE
      ABOIL(1)=ABOIL(1)/(IBACK-IFRONT)
      MSTM1(IFRONT)=ABOIL(1)/2.*P43(IFRONT)*(T(IFRONT,3)-T(IFRONT,4))
     1/HSTM(1)
      MSTM1(IBACK)=ABOIL(1)/2.*P43(IBACK)*(T(IBACK,3)-T(IBACK,4))
     1/HSTM(1)
      STEAM1=MSTM1(IFRONT)+MSTM1(IBACK)
      JFRONT=IFRONT+1
      JBACK=IBACK-1
      DO 425 I=JFRONT,JBACK
      MSTM1(I)=ABOIL(1)*P43(I)*(T(I,3)-T(I,4))/HSTM(1)
      STEAM1=STEAM1+MSTM1(I)
  425 CONTINUE
      TSTM(1)=TSTM(1)-460.
      ABOIL(1)=ABOIL(1)*(IBACK-IFRONT)
      QTOT=STEAM1*HSTM(1)
      WRITE(6,32) TSTM(1),PSTM(1),HSTM(1),ABOIL(1)
      WRITE(6,77) FRONT,BACK
      WRITE(6,58) STEAM1
      WRITE(6,76) QTOT
      WRITE(6,59)
      II=1
      DO 430 I=1,5
      LIM=10*I
      IPRINT=MIN0(LIM,N)
      WRITE(6,44)(Z(J),J=II,IPRINT)
      WRITE(6,61)(MSTM1(J),J=II,IPRINT)
      IF (IPRINT.GE.N) GO TO 435
      II=IPRINT+1
  430 CONTINUE
  435 CONTINUE
C  CALCULATE AND PRINT FRACTION OF STEAM GENERATION DUE TO CONVECTION
C  AND TO RADIATION
      QCONV(IFRONT)=HCONV(IFRONT)*P2*(T(IFRONT,2)-T(IFRONT,3))
      RADST(IFRONT)=RADIN(IFRONT)/2.
      QTOT=ABS(QCONV(IFRONT))+ABS(RADST(IFRONT))
      QCONV(IFRONT)=QCONV(IFRONT)/QTOT
      RADST(IFRONT)=RADST(IFRONT)/QTOT
      QCONV(IBACK)=HCONV(IBACK)*P2*(T(IBACK,2)-T(IBACK,3))
      RADST(IBACK)=RADIN(IBACK)/2.
      QTOT=ABS(QCONV(IBACK))+ABS(RADST(IBACK))
      QCONV(IBACK)=QCONV(IBACK)/QTOT
      RADST(IBACK)=RADST(IBACK)/QTOT
      DO 440 I=JFRONT,JBACK
      QCONV(I)=HCONV(I)*AREAR*(T(I,2)-T(I,3))
      RADST(I)=RADIN(I)
      QTOT=ABS(QCONV(I))+ABS(RADST(I))
      RADST(I)=RADST(I)/QTOT
      QCONV(I)=QCONV(I)/QTOT
      RADIN(I)=RADIN(I)/QTOT
  440 CONTINUE
      II=1
      DO 445 I=1,5
      LIM=10*I
      IPRINT=MIN0(LIM,N)
      WRITE(6,62)
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      WRITE(6,44) (Z(J),J=II,IPRINT)
      WRITE(6,63) (QCONV(J),J=II,IPRINT)
      WRITE(6,64) (RADST(J),J=II,IPRINT)
      IF (IPRINT.GE.N) GO TO 450
      II=IPRINT+1
  445 CONTINUE
  450 CONTINUE
      IF (TYPE.EQ.2) GO TO 460
C  STEAM GENERATION IN CONVECTION BOILER....ASSUME FLOW OVER STAGGERED
C  WATER TUBES....PROPERTIES WILL BE BASED UPON FILM CONDITIONS
  455 CPAVG=(0.24*MSEC(N)+CPOUT*MJET(N))/(MSEC(N)+MJET(N))
      TAVG=TDATUM+(0.24*MSEC(N)*(T(N,2)-TDATUM)+CPOUT*MJET(N)*(T(N,1)
     1-TDATUM))/(CPAVG*(MSEC(N)+MJET(N)))
      TGAS=TAVG
      TAVG=0.5*(TAVG+TSTM(2))
C  USE THE EUCKEN EQUATIONS TO ESTIMATE CONDUCTIVITY AND VISCOSITY
      FACTOR=TAVG**1.5/(225.+TAVG)
      KAIR=9.26E-4*FACTOR
      MUAIR=2.694E-3*FACTOR
      RHOAIR=PRESS/RAIR/TAVG
      VCONV=(MSEC(N)+MJET(N))/AAUG/RHOAIR
      HTUBES=0.287*KAIR/DTUBE*(RHOAIR*VCONV*DTUBE/MUAIR)**0.6
C  IT HAS BEEN ASSUMED THAT THE JET AND SECONDARY FLOW ARE COMPLETELY
C  MIXED BY THE TIME THEY REACH THE CONVECTION BOILER
      QSTM2=HTUBES*ABOIL(2)*(TGAS-TSTM(2))
      STEAM2=QSTM2/HSTM(2)
      TSTM(2)=TSTM(2)-460.
      TGAS=TGAS-460.
      DTUBE=12.*DTUBE
      WRITE(6,33) TSTM(2),PSTM(2),HSTM(2),ABOIL(2),DTUBE
      WRITE(6,66) STEAM2
      WRITE(6,71) TGAS,HTUBES,QSTM2
  460 CONTINUE
C
C  DETERMINE THE ECONOMICS OF GAS TURBINE TEST CELL HEAT RECOVERY
      IF (TYPE.EQ.4) WRITE(6,9)
      WRITE(6,79)
  461 IF (TYPE.EQ.3) GO TO 475
C  FIRST FOR THE WATER-WALL HEAT EXCHANGER
      IF ((IND2.EQ.1).AND.(TYPE.NE.4)) WRITE(6,9)
      IF ((IND2.EQ.2).AND.(TYPE.EQ.4)) WRITE(6,9)
      IF ((IND2.EQ.0).OR.(IND2.GE.7)) WRITE(6,81) PRICE1
      IF ((IND2.GT.0).AND.(IND2.LT.7).AND.(TYPE.EQ.4)) WRITE(6,91)
C  CALCULATE THE VALUE OF THE STEAM GENERATED
      VALUE1=0.365E-3*STEAM1*HSTM(1)*TIME*COST
C  CALCULATE THE PRESENT VALUE OF THE SAVINGS ACCUMULATED OVER THE
C  ECONOMIC LIFE OF THE HEAT RECOVERY HEAT EXCHANGER
      PV(1)=VALUE1*RATIO
      IF (PV(1).LT.0.) PV(1)=0.
      SIR(1)=PV(1)/PRICE1
      DO 465 I=2,25
      PV(I)=PV(I-1)+VALUE1*RATIO**I
      IF (PV(I).LT.0.) PV(I)=0.
      SIR(I)=PV(I)/PRICE1
  465 CONTINUE
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      IF ((IND2.EQ.0).OR.(IND2.GE.7)) WRITE(6,82) DISC,COST,ESC
      WRITE(6,83)
      DO 470 I=1,5
      J=5*I
      WRITE(6,84) J,TIME,PV(J),SIR(J)
  470 CONTINUE
  475 IF (TYPE.EQ.2) GO TO 495
C  THEN FOR THE CONVECTION HEAT EXCHANGER
      IF ((IND2.EQ.3).AND.(TYPE.NE.4)) WRITE(6,9)
      IF ((IND2.EQ.4).AND.(TYPE.EQ.4)) WRITE(6,9)
      IF ((IND2.EQ.0).OR.(IND2.GE.7)) WRITE(6,88) PRICE2
      IF ((IND2.GT.0).AND.(IND2.LT.7).AND.(TYPE.EQ.4)) WRITE(6,92)
C  AS ABOVE, CALCULATE THE VALUE OF THE STEAM GENERATED
      VALUE1=0.365E-3*STEAM2*HSTM(2)*TIME*COST
      PV(1)=VALUE1*RATIO
      IF (PV(1).LT.0.) PV(1)=0.
      SIR(1)=PV(1)/PRICE2
      DO 480 I=2,25
      PV(I)=PV(I-1)+VALUE1*RATIO**I
      IF (PV(I).LT.0.) PV(I)=0.
      SIR(I)=PV(I)/PRICE2
  480 CONTINUE
      IF ((IND2.EQ.0).OR.(IND2.GE.7)) WRITE(6,87) DISC,COST,ESC
      WRITE(6,83)
      DO 485 I=1,5
      J=5*I
      WRITE(6,84) J,TIME,PV(J),SIR(J)
  485 CONTINUE
  495 TIME=2.*TIME
      IF (IND2.EQ.3) TIME=3.
      IF (IND2.EQ.4) TIME=5.
      IF (IND2.EQ.5) TIME=8.
      IND2=IND2+1
      IF (IND2.LT.7) GO TO 461
  500 STOP
    1 FORMAT(I5)
    2 FORMAT(3F10.0,2F10.3)
    3 FORMAT(2F10.1)
    4 FORMAT(4F10.1)
    6 FORMAT(6F10.2)
    7 FORMAT(2F10.3)
    8 FORMAT(4F10.1,F10.3)
    9 FORMAT(1H1)
   11 FORMAT(1H1,5X,"AUGMENTER GEOMETRY")
   12 FORMAT(1H0,10X,"INITIAL AREA OF JET = ",F5.2," SQFT",/11X,"CROSS S
     1ECTIONAL AREA OF AUGMENTER = ",F5.1," SQFT",/11X,"LENGTH OF AUGMEN
     2TER = ",F5.1," FT",/11X,"THICKNESS OF AUGMENTER WALLS = ",F5.3," I
     3N",/11X,"THICKNESS OF ACOUSTIC PILLOWS = ",F5.2," IN"//)
   13 FORMAT(1H ,5X,"PHYSICAL CHARACTERISTICS OF JET EXHAUST")
   14 FORMAT(1H0,10X,"MASS FLOW RATE OF JET = ",F4.0," LB/SEC",/11X,"TOT
     1AL TEMPERATURE = ",F5.0," DEGF",/11X,"TOTAL PRESSURE = ",F4.1," PS
     2IA",/11X,"RATIO OF SPECIFIC HEATS = ",F4.2)
   15 FORMAT(1H ,10X,"COMPOSITION OF EXHAUST (PERCENT WEIGHT)")
   17 FORMAT(1H ,15X,"OXYGEN.............",F5.2,/16X,"NITROGEN.........
     1...",F5.2,/16X,"CARBON DIOXIDE......",F5.2,/16X,"CARBON MONOXIDE..
     2...",F5.2,/16X,"WATER VAPOR.........",F5.2,/16X,"HYDROGEN.........
     3...",F5.2,/11X,"LENGTH OF LUMINOUS JET = ",F5.1," FT"//)
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13 FORMAT(1H ,5X,"PHYSICAL CHARACTERISTICS OF SECONDARY FLOW")
19 FORMAT(1H0,10X,"SECONDARY FLOW RATE = ",F5.0," LB/SEC",/11X,"STATI
  1C TEMPERATURE = ",F4.0," DEGF"//)
21 FORMAT(1H ,5X,"HEAT TRANSFER PROPERTIES")
22 FORMAT(1H0,10X,"THERMAL CONDUCTIVITY OF AUGMENTER WALLS = ",F4.1,"
  1 BTU/HR-FT-DEGF")
23 FORMAT(1H ,10X,"THERMAL CONDUCTIVITY OF ACOUSTIC PILLOWS = ",F5.3,
  1" BTU/HR-FT-DEGF")
24 FORMAT(1H ,10X,"EFFECTIVE HUSH HOUSE CHARACTERISTICS")
26 FORMAT(1H ,15X,"TEMPERATURE AT AUGMENTER INLET = ",F4.0," DEGF",/1
  16X,"CONDUCTANCE AT AUGMENTER INLET = ",E9.3," BTU/HR-DEGF",/16X,"T
  2EMPERATURE AT AUGMENTER EXIT = ",F4.0," DEGF",/16X,"CONDUCTANCE AT
  3 AUGMENTER EXIT = ",E9.3," BTU/HR-DEGF"//)
27 FORMAT(1H ,5X,"THE FACILITY HAS NO BOILERS"/)
28 FORMAT(1H1,5X,"THE FACILITY HAS A WATER-WALL BOILER WRAPPED AROUND
  1 THE AUGMENTER"//)
29 FORMAT(1H1,5X,"THE FACILITY HAS A STAGGERED WATER-TUBE BOILER IN T
  1HE GAS PATH AT THE AUGMENTER EXIT")
31 FORMAT(1H1,5X,"THE FACILITY HAS BOTH A WATER-WALL BOILER WRAPPED A
  1ROUND THE AUGMENTER AND",/6X,"A STAGGERED WATER-TUBE BOILER IN THE
  2 GAS PATH AT THE AUGMENTER EXIT"//)
32 FORMAT(1H ,/6X,"WATER-WALL BOILER CHARACTERISTICS",/16X,"STEAM TEM
  1PERATURE = ",F4.0," DEGF",/16X,"STEAM PRESSURE = ",F5.1," PSIA",/1
  26X,"HEAT OF VAPORIZATION = ",F6.1," BTU/LB",/16X,"TOTAL HEAT TRANS
  3FER AREA = ",F5.0," SQFT"/)
33 FORMAT(1H0,//6X,"CONVECTION WATER-TUBE BOILER CHARACTERISTICS",/16
  1X,"STEAM TEMPERATURE = ",F4.0," DEGF",/16X,"STEAM PRESSURE = ",F5.
  21," PSIA",/16X,"HEAT OF VAPORIZATION = ",F6.1," BTU/LB",/16X,"TOTA
  3L HEAT TRANSFER AREA = ",F5.0," SQFT",/16X,"OUTER DIAMETER OF TUBE
  4S = ",F4.2," IN"/)
34 FORMAT(1H0,5X,"BULK VELOCITIES AT AUGMENTER INLET",/11X,"JET VELOC
  1ITY = ",F5.0," FT/SEC",/11X,"SECONDARY FLOW VELOCITY = ",F4.0," FT
  2/SEC",//6X,"CRAYA-CURTET NUMBER = ",F4.2/)
36 FORMAT(1H0,///6X,"***************************************************
  1*************************************************************"/)
37 FORMAT(1H ,5X,"ITERATION FOR JET SEPARATION POINT IS DIVERGING, AN
  1ALYSIS IS TERMINATED"/)
38 FORMAT(1H ,5X,"****************************************************
  1**********************************************************"/)
39 FORMAT(1H ,5X,"ITERATION FOR JET SEPARATION POINT DID NOT CONVERGE
  1 TO WITHIN ",F3.1," FEET AFTER ",I3," ITERATIONS"/)
41 FORMAT(1H0,5X,"JET EXHAUST REACHES THE AUGMENTER WALL AT AN AXIAL
  1DISTANCE OF ",F4.0," FEET FROM THE INLET"/)
42 FORMAT(1H0,5X,"JET EXHAUST NEVER REACHES THE AUGMENTER WALLS"/)
43 FORMAT(1H0,/6X,"MASS FLOW RATES (LB/SEC) VARIATION WITH AXIAL LOCA
  1TION (FT) AND JET RADIUS (FT)"/)
44 FORMAT(1H ,5X,"DIST FM INLET",1X,10F10.2)
46 FORMAT(1H ,5X,"RADIUS OF JET",1X,10F10.2)
47 FORMAT(1H ,5X,"JET FLOW",6X,10F10.2)
48 FORMAT(1H ,5X,"SECONDARY FLOW",10F10.2)
49 FORMAT(1H ,5X,"ITERATION FOR TEMPERATURES IS DIVERGING, ANALYSIS I
  1S TERMINATED"/)
51 FORMAT(1H ,5X,"ITERATION FOR TEMPERATURES DID NOT CONVERGE TO WITH
  1IN ",F3.1,"DEGF AFTER ",I3," ITERATIONS"/)
52 FORMAT(1H0,/6X,"TEMPERATURE (DEGF) VARIATION WITH AXIAL LOCATION (
  1FT). THE WALL OD INCLUDES ACOUSTIC PILLOWS, IF ANY."/)
53 FORMAT(1H ,5X,"JET TEMP",6X,10F10.1)
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54 FORMAT(1H ,5X,"SEC FLOW TEMP",1X,10F10.1)
56 FORMAT(1H ,5X,"AUG WALL ID",3X,10F10.1)
57 FORMAT(1H ,5X,"AUG WALL OD",3X,10F10.1)
58 FORMAT(1H ,/6X,"TOTAL STEAM GENERATION IN WATER-WALL BOILER = ",E1
  10.4," LB/HR"/)
59 FORMAT(1H0,5X,"WATER-WALL STEAM GENERATION (LB/HR) VARIATION WITH
  1AXIAL LOCATION (FT FROM AUGMENTER INLET)"/)
61 FORMAT(1H ,5X,"STEAM GEN",5X,10F10.1)
62 FORMAT(1H ,/6X,"FRACTION OF WATER-WALL STEAM GENERATION BY CONVECT
  1ION AND BY RADIATION"/)
63 FORMAT(1H ,5X,"CONVECTION",4X,10F10.3)
64 FORMAT(1H ,5X,"RADIATION",5X,10F10.3)
66 FORMAT(1H , /6X,"TOTAL STEAM GENERATION IN CONVECTION WATER-TUBE B
  1OILER = ",E10.4," LB/HR")
67 FORMAT(1H ,5X,"AMBIENT CONDITIONS")
68 FORMAT(1H0,10X,"TEMPERATURE = ",F4.0," DEGF",/11X,"CONVECTIVE FILM
  1 COEFFICIENT = ",F5.1," BTU/HR-SQFT-DEGF"//)
69 FORMAT(1H0,/6X,"BULK VELOCITY OF JET AT AUGMENTER EXIT = ",F5.0,"
  1FT/SEC"/)
71 FORMAT(1H0,5X,"AVERAGE GAS TEMPERATURE AT BOILER INLET = ",F5.0,"
  1DEGF",/6X,"BOILER OVERALL HEAT TRANSFER COEFFICIENT = ",F5.1," BTU
  2/HR-SQFT-DEGF",/6X,"TOTAL HEAT TRANSFERRED = ",E10.4," BTU/HR")
72 FORMAT(1H0,/6X,"EXHAUST GAS EMISSIVITY AND CONVECTIVE FILM COEFFIC
  1IENT (BTU/HR-SQFT-DEGF) BY LOCATION"/)
73 FORMAT(1H ,5X,"FILM COEFF",4X,10F10.2)
74 FORMAT(1H ,5X,"EMISSIVITY",4X,10F10.4)
76 FORMAT(1H ,5X,"TOTAL HEAT TRANSFERRED = ",E10.4," BTU/HR"/)
77 FORMAT(1H ,5X,"THE WATER-WALLS ARE LOCATED ALONG THE SECTION BEGIN
  1NING ",F5.1," FEET FROM THE AUGMENTER INLET",/6X,"AND ENDING AT A
  2DISTANCE OF ",F5.1," FEET FROM THE AUGMENTER INLET"/)
78 FORMAT(F10.1,I10,2F15.2)
79 FORMAT(1H0,//6X,"THE ECONOMICS OF GAS TURBINE TEST CELL ENERGY REC
  1OVERY")
81 FORMAT(1H0,//6X,"THE PURCHASE PRICE OF THE WATER-WALL HEAT EXCHANG
  1ER IS $",F10.2,", PAYABLE WHEN INSTALLATION IS COMPLETE"/)
82 FORMAT(1H0,5X,"THE ACCUMULATED PRESENT VALUE OF SAVINGS RESULTING
  1 ROM THE ADDITION OF THE WATER-WALL BOILER",/6X,"ASSUMING A DISCOU
  2NT RATE OF ",F4.1," PERCENT, A CURRENT STEAM PRICE OF $",F5.2,"/MB
  3TU, AND A",/6X,"STEAM ESCALATION RATE OF "F4.1," PERCENT")
83 FORMAT(1H0,6X,"ECONOMIC",6X,"OPERATION",11X,"ACCUM PV OF",12X,"SIR
  1",/6X,"LIFE (YRS)",5X,"(HRS/DAY)",10X,"STEAM GEN ($)")
84 FORMAT(1H ,8X,I2,12X,F4.2,10X,F14.0,10X,F6.2)
87 FORMAT(1H0,5X,"THE ACCUMULATED PRESENT VALUE OF SAVINGS RESULTING
  1FROM THE ADDITION OF THE CONVECTION BOILER",/6X,"ASSUMING A DISCOU
  2NT RATE OF ",F4.1," PERCENT, A CURRENT STEAM PRICE OF $",F5.2,"/MB
  3TU, AND A",/6X,"STEAM ESCALATION RATE OF ",F4.1," PERCENT")
88 FORMAT(1H0,//6X,"THE PURCHASE PRICE OF THE CONVECTION HEAT EXCHANG
  1ER IS $",F10.2,", PAYABLE WHEN INSTALLATION IS COMPLETE"/)
89 FORMAT(1H0,2X," SOLUTION CONVERGED AFTER ",I3," ITERATIONS TO WITH
  1IN ",F4.2," DEGREES"/)
91 FORMAT(1H0,/6X,"WATER-WALL HEAT EXCHANGER")
92 FORMAT(1H0,/6X,"CONVECTION (WATER TUBE) HEAT EXCHANGER")
   END
```

```
      FUNCTION SPHT(T,I)
C  PROGRAM TO CALCULATE THE MEAN SPECIFIC HEAT BETWEEN T AND 60 DEGF
C  OF A MIXTURE OF GASES....THE GASES CONSIDERED ARE OXYGEN, NITROGEN
C  CARBON MONOXIDE, HYDROGEN, WATER VAPOR, AND CARBON DIOXIDE
C  SPECIFIC HEAT CALCULATED IN BTU/LB-DEGF
      REAL MW,MOLES,N2,NIT(50),MONOX(50)
      COMMON OXY,NIT,DIOX,WATER,MONOX,HYD,LUM
      DIMENSION OXY(50),DIOX(50),WATER(50),HYD(50)
      DIMENSION CP(6)
      DATA TDATUM/520./
      SPHT=0.
      DELTA=T-TDATUM
      O2=OXY(I)
      N2=NIT(I)
      CO=MONOX(I)
      H2=HYD(I)
      H2O=WATER(I)
      CO2=DIOX(I)
C  FIRST CALCULATE THE MEAN SPECIFIC HEAT OF INDIVIDUAL COMPONENTS
C  USING THE RELATIONSHIPS OF SWEIGERT AND BEARDSLEY, REF. GEORGIA
C  INST. OF TECH. BULLETIN 2 (1938)
      CP(1)=(11.515*DELTA-344.*(SQRT(T)-SQRT(TDATUM))+1530.
     1*(ALOG(T)-ALOG(TDATUM)))/DELTA*O2
      CP(2)=(9.47*DELTA-3.47E3*(ALOG(T)-ALOG(TDATUM))-1.16E6
     1*(1./T-1./TDATUM))/DELTA*N2
      CP(3)=(9.46*DELTA-3.29E3*(ALOG(T)-ALOG(TDATUM))-1.07E6
     1*(1./T-1./TDATUM))/DELTA*CO
      CP(4)=(5.76*DELTA+2.89E-4*(T**2-TDATUM**2)+40.*(SQRT(T)
     1-SQRT(TDATUM)))/DELTA*H2
      CP(5)=(19.86*DELTA-1194.*(SQRT(T)-SQRT(TDATUM))+7500.
     1*(ALOG(T)-ALOG(TDATUM)))/DELTA*H2O
      CP(6)=(16.2*DELTA-6.53E3*(ALOG(T)-ALOG(TDATUM))-1.41E6
     1*(1./T-1./TDATUM))/DELTA*CO2
C  THE TOTAL NUMBER OF MOLES IN THE MIXTURE
      MOLES=O2+N2+CO+H2+H2O+CO2
C  THE MOLECULAR WEIGHT OF THE MIXTURE
      MW=(O2*32.+N2*28.+CO*28.+H2*2.+H2O*18.+CO2*44.)/MOLES
C  ALLOWING THE MEAN SPECIFIC HEAT TO BE DETERMINED
      DO 5 J=1,6
      SPHT=SPHT+CP(J)/MOLES/MW
    5 CONTINUE
      RETURN
      END
```

```
      FUNCTION EMISS(T,L,I)
C   PROGRAM TO CALCULATE THE EMISSIVITY OF A MIXTURE OF COMBUSTION GASES.
C   CARBON DIOXIDE, WATER VAPOR, AND CARBON MONOXIDE ALL CONTRIBUTE AND
C   THEIR INDIVIDUAL EMISSIVITIES ARE OBTAINED FROM CURVE FITS OF THE
C   TABLES OF MCADAMS, "HEAT TRANSMISSION", MCGRAW-HILL,(1954)
      REAL L,MOLES,N2,NIT(50),MONOX(50)
      COMMON OXY,NIT,DIOX,WATER,MONOX,HYD,LUM
      DIMENSION OXY(50),DIOX(50),WATER(50),HYD(50)
      DATA DELTA/0./
C
C   IF SEGMENT "I" OF THE JET EXHAUST IS LUMINOUS, SET THE EMISSIVITY
C   EQUAL TO ONE
      IF (I.GT.LUM) GO TO 5
      EMISS=1.
      GO TO 50
C
    5 O2=OXY(I)
      N2=NIT(I)
      CO=MONOX(I)
      H2=HYD(I)
      H2O=WATER(I)
      CO2=DIOX(I)
C   CALCULATE THE PARTIAL PRESSURE OF INDIVIDUAL GASES IN ATMOSPHERES
C   ASSUMING A TOTAL PRESSURE OF ONE ATMOSPHERE
      MOLES=CO2+H2O+CO+O2+N2+H2
      PCO2=CO2/MOLES
      PH2O=H2O/MOLES
      PCO=CO/MOLES
C   THE INDEPENDENT VARIABLE IS PARTIAL PRESSURE TIMES MEAN BEAM LENGTH
      PCO2L=PCO2*L
      PH2OL=PH2O*L
      PCOL=PCO*L
C
C   CALCULATE EMISSIVITY OF CARBON DIOXIDE
      IF (PCO2L.LE.0.) GO TO 10
      POWER=-0.721+0.215*ALOG10(PCO2L)
      EMAX=-0.04+10.**POWER
      TMAX=2600.+800.*ALOG10(EMAX)
      POWER=((T-TMAX)/2800.)**2
      POWER=EXP(-POWER)-1.
      ECO2=EMAX*10.**POWER
C   CORRECT FOR OVERLAP WITH WATER VAPOR
      ECO2=ECO2-DELTA
      GO TO 15
   10 ECO2=0.
C   CALCULATE EMISSIVITY OF WATER VAPOR
   15 IF (PH2OL.LE.0.) GO TO 20
      EMAX=2.+ALOG10(PH2OL)
      EMAX=-2.097+0.821*EMAX-0.1115*EMAX*(EMAX-1.)-0.00567*EMAX
     1*(EMAX-1.)*(EMAX-2.)
      POWER=(EMAX-0.59)*(T+5000.)/7000.+0.59
      EH2O=10.**POWER
C   CORRECT FOR PARTIAL PRESSURE OTHER THAN ZERO
      EH2O=EH2O*(1.+(0.62-0.1*ALOG(PH2OL))*PH2O)
      GO TO 25
   20 EH2O=0.
C   CALCULATE EMISSIVITY OF CARBON MONOXIDE
```

```
   25 IF (PCOL.LE.0.) GO TO 30
      POWER=-0.8477+0.1809*ALOG10(PCOL)
      EMAX=-0.0403+10.**POWER
       TMAX=1600.+3280.*(0.122-EMAX)
      POWER=((T-TMAX)/1800.)**2
      POWER=-1.+EXP(-POWER)
      ECO=EMAX*10.**POWER
C  CORRECT EMISSIVITY OF CO FOR OVERLAP WITH CO2
      ECO=0.7*ECO
      GO TO 35
   30 ECO=0.
C
C  CALCULATE THE TOTAL EMISSIVITY OF THE COMBUSTION GASES
   35 EMISS=ECO2+EH2O+ECO
      IF (EMISS.LE.1.) GO TO 50
      WRITE(6,1)
      WRITE(6,2)
      WRITE(6,3)
   50 RETURN
    1 FORMAT(1H0,////6X,"***********************************************
     1*****************************************************************")
    2 FORMAT(1H ,//6X,"EMISSIVITY GREATER THAN ONE.....THE GAS COMPOSITI
     1ON IS PROBABLY INCORRECT")
    3 FORMAT(1H ,//6X,"************************************************
     1**************************************************************"//)
      END
```

```
      SUBROUTINE SHAPE(RI,RO,L,F,N)
C  PROGRAM TO CALCULATE THE SHAPE FACTORS FOR RADIANT HEAT TRANSFER
C  BETWEEN CONCENTRIC CYLINDERS OF VARIOUS LENGTHS AND ASPECTS
C  THE EXPRESSIONS USED HERE WERE DEVELOPED FROM EXPRESSIONS FOR SHAPE
C  FACTORS DERIVED BY LEUENBERGER AND PERSON, "COMPILATION OF RADIATION
C  SHAPE FACTORS FOR CYLINDRICAL ASSEMBLIES", ASME PAPER 56-A-144 (1956)
      REAL L,L1
      DIMENSION F(50,50),RI(50),F1(2)
      DATA PI/3.1416/
C
C  FIRST CALCULATE SHAPE FACTORS OF DIRECTLY OPPOSED SEGMENTS
      DO 5 I=1,N
      IF (RI(I).LT.RO) GO TO 2
      F(I,I)=1.00
      GO TO 5
    2 Z=L
      IF ((I.EQ.1).OR.(I.EQ.N)) Z=0.5*L
      A=Z**2-RO**2+RI(I)**2
      B=Z**2+RO**2-RI(I)**2
      C=A/B
      D=Z**2+RO**2+RI(I)**2
      F(I,I)=1.-1./PI*(ACOS(C)-0.5/RI(I)/Z*(SQRT(D**2-(2.*RI(I)*RO)**2)
     1*ACOS(C*RI(I)/RO)+A*ASIN(RI(I)/RO)-0.5*PI*B))
    5 CONTINUE
C  AND THEN ALL OTHERS
      DO 40 I=1,N
      DO 35 J=1,N
      IF (I.EQ.J) GO TO 35
      IF (RI(I).LT.RO) GO TO 10
      F(I,J)=0.
      GO TO 35
   10 CONTINUE
      IF (J.GT.I) GO TO 20
C
C  FIRST, SEGMENTS RADIATING "UPSTREAM"
      JJ=J+1
      II=I-1
      L1=(I-J+1)*L
      IF (I.EQ.N) L1=L1-0.5*L
      DO 15 K=1,2
      A=L1**2-RO**2+RI(I)**2
      B=L1**2+RO**2-RI(I)**2
      C=A/B
      D=L1**2+RO**2+RI(I)**2
      F1(K)=RI(I)*L1/PI/(RO**2-RI(I)**2)*(ACOS(C)-0.5/RI(I)/L1*(SQRT
     1(D**2-(2.*RI(I)*RO)**2)*ACOS(C*RI(I)/RO)+A*ASIN(RI(I)/RO)
     2-0.5*PI*B))
      L1=L1-L
   15 CONTINUE
      Z=L
      IF (I.EQ.N) Z=0.5*L
      F(I,J)=0.5*(1.-F(I,I)-(RO**2-RI(I)**2)/RI(I)/Z*(F1(1)-F1(2)))
C  NOTE THAT THESE ARE COMBINED SHAPE FACTORS AND NEED TO BE SEPARATED
      GO TO 35
C
   20 CONTINUE
C  AND THEN SEGMENTS RADIATING "DOWNSTREAM"
```

AD-A139 457 THERMAL ENERGY RECOVERY IN GAS TURBINE ENGINE TEST CELLS(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA C A KODRES NOV 83 NCEL-TN-1679

2/2

UNCLASSIFIED F/G 10/1 NL

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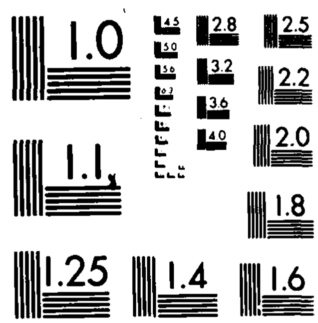
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4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

```
      II=I+1
      JJ=J-1
      L1=(J-I+1)*L
      IF (I.EQ.1) L1=L1-0.5*L
      DO 25 K=1,2
      A=L1**2-RO**2+RI(I)**2
      B=L1**2+RO**2-RI(I)**2
      C=A/B
      D=L1**2+RO**2+RI(I)**2
      F1(K)=RI(I)*L1/PI/(RO**2-RI(I)**2)*(ACOS(C)-0.5/RI(I)/L1*(SQRT
     1(D**2-(2.*RI(I)*RO)**2)*ACOS(C*RI(I)/RO)+A*ASIN(RI(I)/RO)
     2-0.5*PI*B))
      L1=(J-I)*L
   25 CONTINUE
      Z=L
      IF (I.EQ.1) Z=0.5*L
      F(I,J)=0.5*(1.-F(I,I)-(RO**2-RI(I)**2)/RI(I)/Z*(F1(1)-F1(2)))
      IF (J.LE.II) GO TO 35
      DO 30 K=II,JJ
      F(I,J)=F(I,J)-F(I,K)
   30 CONTINUE
   35 CONTINUE
   40 CONTINUE
C
C   SEPARATE THE "UPSTREAM" SHAPE FACTORS
      DO 55 I=3,N
      JJ=I-2
      LL=I-1
      DO 50 M=1,JJ
      J=JJ-M+1
      KK=J+1
      DO 45 K=KK,LL
      F(I,J)=F(I,J)-F(I,K)
   45 CONTINUE
   50 CONTINUE
   55 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SHAPE1(R,Z,F,N)
C   PROGRAM TO CALCULATE THE SHAPE FACTOR FOR RADIANT HEAT TRANSFER
C   BETWEEN FINITE RING AREAS ON INTERIOR OF RIGHT CIRCULAR CYLINDER
C   REF...HOTTEL AND SAROFIM, "RADIATIVE TRANSFER", MCGRAW-HILL, (1967)
      DIMENSION F(50,50)
      DATA PI/3.1416/
C
      DO 10 I=1,N
      DO 10 J=1,N
      IF (I.EQ.J) GO TO 5
      A=IABS(I-J)*Z
      B=(IABS(I-J)-1.)*Z
      C=(IABS(I-J)+1.)*Z
      F(I,J)=PI/2.*(B**2-B*SQRT(4.*R**2+B**2)-2.*(A**2-A*SQRT(4.*R**2
     1+A**2))+C**2-C*SQRT(4.*R**2+C**2))
      GO TO 8
    5 F(I,J)=PI*(2.*R*Z+Z**2-Z*SQRT(4.*R**2+Z**2))
    8 AREA=2.*PI*R*Z
      F(I,J)=F(I,J)/AREA
   10 CONTINUE
      RETURN
      END
```

TYPICAL RESULTS

This particular summary is for the J79 at A/B being tested in the hush house at the Marine Corps Air Station, El Toro, Calif. Waterwalls and a water tube boiler are examined together in order to illustrate the capabilities of the model.

```
AUGMENTER GEOMETRY

     INITIAL AREA OF JET =  4.20 SQFT
     CROSS SECTIONAL AREA OF AUGMENTER =  63.0 SQFT
     LENGTH OF AUGMENTER =  67.0 FT
     THICKNESS OF AUGMENTER WALLS =  .111 IN
     THICKNESS OF ACOUSTIC PILLOWS =  6.00 IN

PHYSICAL CHARACTERISTICS OF JET EXHAUST

     MASS FLOW RATE OF JET = 180. LB/SEC
     TOTAL TEMPERATURE = 3060. DEGF
     TOTAL PRESSURE = 36.8 PSIA
     RATIO OF SPECIFIC HEATS = 1.40
     COMPOSITION OF EXHAUST (PERCENT WEIGHT)
          OXYGEN.............. 0.00
          NITROGEN............75.00
          CARBON DIOXIDE......16.00
          CARBON MONOXIDE..... 1.00
          WATER VAPOR......... 8.00
          HYDROGEN............ 0.00
     LENGTH OF LUMINOUS JET =    0.0 FT

PHYSICAL CHARACTERISTICS OF SECONDARY FLOW

     SECONDARY FLOW RATE = 1130. LB/SEC
     STATIC TEMPERATURE =  75. DEGF

AMBIENT CONDITIONS

     TEMPERATURE =  75. DEGF
     CONVECTIVE FILM COEFFICIENT =   5.0 BTU/HR-SQFT-DEGF

HEAT TRANSFER PROPERTIES

     THERMAL CONDUCTIVITY OF AUGMENTER WALLS = 30.0 BTU/HR-FT-DEGF
     THERMAL CONDUCTIVITY OF ACOUSTIC PILLOWS =  .050 BTU/HR-FT-DEGF
     EFFECTIVE HUSH HOUSE CHARACTERISTICS
          TEMPERATURE AT AUGMENTER INLET =  70. DEGF
          CONDUCTANCE AT AUGMENTER INLET =  .500E+03 BTU/HR-DEGF
          TEMPERATURE AT AUGMENTER EXIT = 150. DEGF
          CONDUCTANCE AT AUGMENTER EXIT =  .500E+03 BTU/HR-DEGF


BULK VELOCITIES AT AUGMENTER INLET
     JET VELOCITY = 2928. FT/SEC
     SECONDARY FLOW VELOCITY = 259. FT/SEC

CRAYA-CURTET NUMBER =  .62


JET EXHAUST REACHES THE AUGMENTER WALL AT AN AXIAL DISTANCE OF  24. FEET FROM THE INLET
```

MASS FLOW RATES (LB/SEC) VARIATION WITH AXIAL LOCATION (FT) AND JET RADIUS (FT)

DIST FM INLET	0.00	3.72	7.44	11.17	14.89	18.61	22.33	26.06	29.78	33.50
RADIUS OF JET	1.16	1.64	2.14	2.64	3.14	3.66	4.19	4.48	4.48	4.48
JET FLOW	190.00	262.61	375.07	518.86	695.92	908.57	1159.60	1310.00	1310.00	1310.00
SECONDARY FLOW	1130.00	1047.39	934.93	791.14	614.08	401.43	150.40	.00	.00	.00

MASS FLOW RATES (LB/SEC) VARIATION WITH AXIAL LOCATION (FT) AND JET RADIUS (FT)

DIST FM INLET	37.22	40.94	44.67	48.39	52.11	55.83	59.56	63.28	67.00
RADIUS OF JET	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48	4.48
JET FLOW	1310.00	1310.00	1310.00	1310.00	1310.00	1310.00	1310.00	1310.00	1310.00
SECONDARY FLOW	.00	.00	.00	.00	.00	.00	.00	.00	.00

SOLUTION CONVERGED AFTER 32 ITERATIONS TO WITHIN .84 DEGREES

TEMPERATURE (DEGF) VARIATION WITH AXIAL LOCATION (FT). THE WALL OD INCLUDES ACOUSTIC PILLOWS, IF ANY.

DIST FM INLET	0.00	3.72	7.44	11.17	14.89	18.61	22.33	26.05	29.78	33.50
JET TEMP	2248.9	1830.4	1417.1	1096.2	861.3	690.0	563.4	509.5	509.7	509.7
SEC FLOW TEMP	75.0	75.3	75.6	75.8	75.9	76.1	76.5			
AUG WALL ID	117.4	235.2	264.7	229.7	190.6	169.6	173.9	493.5	498.9	497.3
AUG WALL OD	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0

TEMPERATURE (DEGF) VARIATION WITH AXIAL LOCATION (FT). THE WALL OD INCLUDES ACOUSTIC PILLOWS, IF ANY.

DIST FM INLET	37.22	40.94	44.67	48.39	52.11	55.83	59.56	63.28	67.00
JET TEMP	509.4	509.1	508.8	508.5	508.3	508.1	508.0	508.2	508.8
AUG WALL ID	353.2	353.2	353.2	353.2	353.2	353.2	353.2	353.2	352.6
AUG WALL OD	352.0	352.0	352.0	352.0	352.0	352.0	352.0	352.0	352.0

BULK VELOCITY OF JET AT AUGMENTER EXIT = 508. FT/SEC

EXHAUST GAS EMISSIVITY AND CONVECTIVE FILM COEFFICIENT (BTU/HR-SQFT-DEGF) BY LOCATION

DIST FM INLET	0.00	3.72	7.44	11.17	14.89	18.61	22.33	26.06	29.78	33.50
FILM COEFF	33.15	17.87	10.71	7.70	5.19	5.45	5.58	23.61	23.61	23.61
EMISSIVITY	.1711	.2048	.1997	.1940	.1646	.1510	.1376	.1241	.1164	.1164

EXHAUST GAS EMISSIVITY AND CONVECTIVE FILM COEFFICIENT (BTU/HR-SQFT-DEGF) BY LOCATION

DIST FM INLET	37.22	40.94	44.67	48.39	52.11	55.83	59.56	63.28	67.00
FILM COEFF	23.61	23.61	23.61	23.61	23.60	23.60	23.60	23.61	23.61
EMISSIVITY	.1164	.1164	.1164	.1164	.1164	.1164	.1164	.1164	.1164

THE FACILITY HAS BOTH A WATER-WALL BOILER WRAPPED AROUND THE AUGMENTER AND
A STAGGERED WATER-TUBE BOILER IN THE GAS PATH AT THE AUGMENTER EXIT

WATER-WALL BOILER CHARACTERISTICS
STEAM TEMPERATURE = 352. DEGF
STEAM PRESSURE = 138.2 PSIA
HEAT OF VAPORIZATION = 869.1 BTU/LB
TOTAL HEAT TRANSFER AREA = 950. SQFT

THE WATER-WALLS ARE LOCATED ALONG THE SECTION BEGINNING 40.0 FEET FROM THE AUGMENTER INLET
AND ENDING AT A DISTANCE OF 67.0 FEET FROM THE AUGMENTER INLET

TOTAL STEAM GENERATION IN WATER-WALL BOILER = .4006E+04 LB/HR

TOTAL HEAT TRANSFERRED = .3481E+07 BTU/HR

WATER-WALL STEAM GENERATION (LB/HR) VARIATION WITH AXIAL LOCATION (FT FROM AUGMENTER INLET)

DIST FM INLET	0.00	3.72	7.44	11.17	14.89	18.61	22.33	26.05	29.78	33.50
STEAM GEN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DIST FM INLET	37.22	40.94	44.67	48.39	52.11	55.83	59.56	63.28	67.00	
STEAM GEN	259.7	523.3	516.8	514.0	512.6	512.2	512.6	514.2	130.3	

FRACTION OF WATER-WALL STEAM GENERATION BY CONVECTION AND BY RADIATION

DIST FM INLET	0.00	3.72	7.44	11.17	14.89	18.61	22.33	26.05	29.78	33.50
CONVECTION	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
RADIATION	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

FRACTION OF WATER-WALL STEAM GENERATION BY CONVECTION AND BY RADIATION

DIST FM INLET	37.22	40.94	44.67	48.39	52.11	55.83	59.56	63.28	67.00
CONVECTION	.935	.961	.972	.975	.977	.978	.978	.978	.989
RADIATION	.065	.039	.028	.025	.023	.022	.022	.022	.011

CONVECTION WATER-TUBE BOILER CHARACTERISTICS
STEAM TEMPERATURE = 352. DEGF
STEAM PRESSURE = 138.2 PSIA
HEAT OF VAPORIZATION = 869.1 BTU/LB
TOTAL HEAT TRANSFER AREA = 1520. SQFT
OUTER DIAMETER OF TUBES = 3.00 IN

TOTAL STEAM GENERATION IN CONVECTION WATER-TUBE BOILER = .1320E+05 LB/HR

AVERAGE GAS TEMPERATURE AT BOILER INLET = 509. DEGF
BOILER OVERALL HEAT TRANSFER COEFFICIENT = 48.1 BTU/HR-SQFT-DEGF
TOTAL HEAT TRANSFERRED = .1147E+08 BTU/HR

THE ECONOMICS OF GAS TURBINE TEST CELL ENERGY RECOVERY

THE PURCHASE PRICE OF THE WATER-WALL HEAT EXCHANGER IS $1000000.00, PAYABLE WHEN INSTALLATION IS COMPLETE

THE ACCUMULATED PRESENT VALUE OF SAVINGS RESULTING FROM THE ADDITION OF THE WATER-WALL BOILER
ASSUMING A DISCOUNT RATE OF 10.0 PERCENT, A CURRENT STEAM PRICE OF $ 9.73/MBTU, AND A
STEAM ESCALATION RATE OF 8.0 PERCENT

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	.25	14632.	.01
10	.25	27981.	.03
15	.25	40159.	.04
20	.25	51271.	.05
25	.25	61408.	.06

THE PURCHASE PRICE OF THE CONVECTION HEAT EXCHANGER IS $2000000.00, PAYABLE WHEN INSTALLATION IS COMPLETE

THE ACCUMULATED PRESENT VALUE OF SAVINGS RESULTING FROM THE ADDITION OF THE CONVECTION BOILER
ASSUMING A DISCOUNT RATE OF 10.0 PERCENT, A CURRENT STEAM PRICE OF $ 9.73/MBTU, AND A
STEAM ESCALATION RATE OF 8.0 PERCENT

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	.25	48203.	.02
10	.25	92180.	.05
15	.25	132301.	.07
20	.25	168906.	.08
25	.25	202302.	.10

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	.50	29263.	.03
10	.50	55961.	.06
15	.50	80319.	.08
20	.50	102541.	.10
25	.50	122816.	.12

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	.50	96405.	.05
10	.50	184359.	.09
15	.50	264603.	.13
20	.50	337812.	.17
25	.50	404604.	.20

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	1.00	58527.	.06
10	1.00	111923.	.11
15	1.00	160638.	.16
20	1.00	205083.	.21
25	1.00	245631.	.25

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	1.00	192810.	.10
10	1.00	368718.	.18
15	1.00	529206.	.26
20	1.00	675625.	.34
25	1.00	809208.	.40

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	2.00	117053.	.12
10	2.00	223845.	.22
15	2.00	321276.	.32
20	2.00	410165.	.41
25	2.00	491262.	.49

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	2.00	385621.	.19
10	2.00	737437.	.37
15	2.00	1058412.	.53
20	2.00	1351249.	.68
25	2.00	1618416.	.81

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	3.00	175580.	.18
10	3.00	335768.	.34
15	3.00	481914.	.48
20	3.00	615248.	.62
25	3.00	736893.	.74

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	3.00	578431.	.29
10	3.00	1106155.	.55
15	3.00	1587618.	.79
20	3.00	2026874.	1.01
25	3.00	2427623.	1.21

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	5.00	292633.	.29
10	5.00	559613.	.56
15	5.00	803169.	.80
20	5.00	1025413.	1.03
25	5.00	1228155.	1.23

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	5.00	964052.	.49
10	5.00	1843592.	.92
15	5.00	2645030.	1.32
20	5.00	3378123.	1.69
25	5.00	4046039.	2.02

WATER-WALL HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	8.00	468213.	.47
10	8.00	895381.	.90
15	8.00	1285103.	1.29
20	8.00	1640660.	1.64
25	8.00	1965048.	1.97

CONVECTION (WATER TUBE) HEAT EXCHANGER

ECONOMIC LIFE (YRS)	OPERATION (HRS/DAY)	ACCUM PV OF STEAM GEN ($)	SIR
5	8.00	1542483.	.77
10	8.00	2949748.	1.47
15	8.00	4233649.	2.12
20	8.00	5404997.	2.70
25	8.00	6473663.	3.24

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NAVSECGRUACT Facil. Off., Galeta Is. Panama Canal; PWO, Adak AK; PWO, Edzell Scotland; PWO, Puerto Rico; PWO, Torri Sta, Okinawa; Security Offr, Winter Harbor ME
NAVSECSTA PWD - Engr Div, Wash., DC
NAVSHIPREPFAC Library, Guam; SCE Subic Bay
NAVSHIPYD (Code 452) Shop 02 Portsmouth, VA; Bremerton, WA (Carr Inlet Acoustic Range); Code 134, Pearl Harbor, HI; Code 202.4, Long Beach CA; Code 202.5 (Library) Puget Sound, Bremerton WA; Code 280, Mare Is., Vallejo, CA; Code 280.28 (Goodwin), Vallejo, CA; Code 380, Portsmouth, VA; Code 382.3, Pearl Harbor, HI; Code 400, Puget Sound; Code 410, Mare Is., Vallejo CA; Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; Code 453 (Util. Supr), Vallejo CA; Commander, Philadelphia, PA; L.D. Vivian; Library, Portsmouth NH; PW Dept, Long Beach, CA; PWD (Code 420) Dir Portsmouth, VA; PWD (Code 450-HD) Portsmouth, VA; PWD (Code 453-HD) SHPO 03, Portsmouth, VA; PWD (Code 457-HD) Shop 07, Portsmouth, VA; PWD (Code 460) Portsmouth, VA; PWO, Bremerton, WA; PWO, Mare Is.; PWO, Puget Sound; SCE, Pearl Harbor HI; Security Offr, Bremerton WA; Security Offr, Charleston SC; Security Offr, Vallejo CA; Tech Library, Vallejo, CA
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NAVSURFWPNCEN G-52 (Duncan) Dahlgren, VA; PWO, White Oak, Silver Spring, MD; Silver Spring MD
NAVTECHTRACEN SCE, Pensacola FL
NAVTELCOMMCOM Code 53, Washington, DC; Security Offr, Washington DC
NAVUSEAWARENGSTA Security Spec (Code 01A) Key-ort, WA
NAVWARCOL President, Newport, RI
NAVWPNCEN Code 24 (Dir Safe & Sec) China Lake, CA; Code 2636 China Lake; Cmdr, China Lake, CA; Code 26605 China Lake CA; Code 3276 China Lake, CA; Code 623 China Lake CA; PWO (Code 266) China Lake, CA; ROICC (Code 702), China Lake CA
NAVWPNEVALFAC CO Kirtland AFB, NM; Sec Offr, Kirtland AFB, NM; Technical Library, Albuquerque NM
NAVWPNSTA (Clebak) Colts Neck, NJ; Code 09, Concord, CA; Code 092, Colts Neck NJ; Code 092, Concord CA; Code 092A, Seal Beach, CA; Maint. Control Dir., Yorktown VA; Nav Wpns Hndlng Cen (Code 8052) Colts Neck NJ; Nuc Safe Offr, Yorktown, VA
NAVWPNSTA PW Office Yorktown, VA
NAVWPNSTA PWD - Maint Control Div, Charleston, SC; PWD - Maint. Control Div., Concord, CA; PWD - Supr Gen Engr, Seal Beach, CA; PWO, Charleston, SC; PWO, Seal Beach CA; Safety Br, Concord, CA; Sec Offr, Charleston, SC; Security Offr, Colts Neck NJ; Security Offr, Concord CA; Security Offr., Yorktown, VA; Special Wpns Offr, Concord, CA; Wpns Fac Offr, Colts Neck, NJ; Wpns Offr, Charleston, SC; Wpns Offr, Colts Neck, NJ; Wpns Offr, Yorktown, VA
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NCBU 405 OIC, San Diego, CA
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NCBC Code 10 Davisville, RI; Code 15, Port Hueneme CA; Code 155, Port Hueneme CA; Code 1552 (Brazele) Port Hueneme, CA; Code 155B (Nishimura) Port Hueneme, CA; Code 156, Port Hueneme, CA; Code 156F (Volpe) Port Hueneme, CA; Code 1571, Port Hueneme, CA; Code 25111 Port Hueneme, CA; Code 400, Gulfport MS; Code 430 (PW Engrng) Gulfport, MS; Code 470.2, Gulfport, MS; NEESA Code 252 (P Winters) Port Hueneme, CA; PWO (Code 80) Port Hueneme, CA; PWO, Davisville RI; PWO, Gulfport, MS
NCBU 411 OIC, Norfolk VA
NCR 20, Code R70; 20, Commander; 20th, Code R50; 30th Det, OIC, Diego Garcia I; 31, Cmdr, Port Hueneme, CA; 31, Code R50, Port Hueneme, CA
NMCB 3, SWC D. Wellington; 74, CO; FIVE, Operations Dept; Forty, CO; THREE, Operations Off.
NOAA (Dr. T. Mc Guinness) Rockville, MD; (M. Ringenbach), Rockville, MD; Library Rockville, MD
NOAA DATA BUOY OFFICE Engrng Div (Riannie) Bay St. Louis, MS
NORDA CO, Bay St. Louis, MS; Code 350 (Swenson) Bay St. Louis, MS; Code 410 Bay St. Louis, MS; Code 440 (Ocean Rsch Off) Bay St. Louis MS; Code 500, (Ocean Prog Off-Ferer) Bay St. Louis, MS
NRL Code 1226.1, Washington DC; Code 5800 Washington, DC; Code 5843 (F. Rosenthal) Washington, DC; Code 8441 (R.A. Skop), Washington DC; Griffith, Wash., DC
NROTC J.W. Stephenson, UC, Berkeley, CA
NSC CO, Biomedical Rsch Lab, Oakland CA; Code 44 (Security Officer) Oakland, CA; Code 54.1 Norfolk, VA; Nuc Wpns Supply Dept, Security Offr; Security Offr, Hawaii
NSD SCE, Subic Bay, R.P.
NSF Polar Info Service
NSWSES Code 0150 Port Hueneme, CA
NTC OICC, CBU-401, Great Lakes IL
NTSB Chairman, Wash DC
NUCLEAR REGULATORY COMMISSION Off Prog Dev Div of Safeguards, Washington, DC; T.C. Johnson, Washington, DC
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ONR Cagle, Pasadena, CA; Central Regional Office, Boston, MA; Code 221, Arlington VA; Code 461, Arlington VA (McGregor); Code 481, Bay St. Louis, MS; Code 485 (Silva) Arlington, VA; Code 700F Arlington VA; Security Offr, Arlington VA
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PHIBCB 1 P&E, San Diego, CA; 1, CO San Diego, CA
PMTC Code 3144, (E. Good) Point Mugu, CA; Code 3331 (S. Opatowsky) Point Mugu, CA; Code 4253-3, Point Mugu, CA; EOD Mobile Unit, Point Mugu, CA
POMFLANT Dir Mgmnt Staff, Charleston, SC; Security Offr, Charleston, SC

PWC ACE Office Norfolk, VA; CO Norfolk, VA; CO, (Code 10), Oakland, CA; CO, Great Lakes IL; CO, Pearl Harbor HI; Code 10, Great Lakes, IL; Code 105 Oakland, CA; Code 110, Great Lakes, IL; Code 110, Oakland, CA; Code 120, Oakland CA; Code 128, Guam; Code 154 (Library), Great Lakes, IL; Code 200, Great Lakes IL; Code 200, Guam; Code 30V, Norfolk, VA; Code 400, Great Lakes, IL; Code 400, Pearl Harbor, HI; Code 400, San Diego, CA; Code 420, Great Lakes, IL; Code 420, Oakland, CA; Code 424, Norfolk, VA; Code 500 Norfolk, VA; Code 505A Oakland, CA; Code 600, Great Lakes, IL; Code 610, San Diego Ca; Code 700, Great Lakes, IL; Code 700, Norfolk, VA; Code 700, San Diego, CA; Dir of Security, Subic Bay RP; Library, Code 120C, San Diego, CA; Library, Guam; Library, Norfolk, VA; Library, Pearl Harbor, HI; Library, Pensacola, FL; Library, Subic Bay, R.P.; Library, Yokosuka JA; Util Dept (R Pascua) Pearl Harbor, HI; Utilities Officer, Guam

SPCC PWO (Code 120) Mechanicsburg PA

SUBRESUNIT OIC Seacliff, San Diego; OIC Turtle, San Diego

SUPANX PWO, Williamsburg VA

SWFPAC Security Offr, Bremerton, WA; Wpns Offr (SPB30) Bremerton, WA

TRIREFFAC SCE Bremerton, WA

TVA Solar Group, Arnold, Knoxville, TN

UCT ONE OIC, Norfolk, VA

UCT TWO OIC, Port Hueneme CA

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US NAVAL FORCES Korea (ENJ-P&O)

USAF HOSPITAL Castle AFB, CA

USAF REGIONAL HOSPITAL Fairchild AFB, WA

USAF SCHOOL OF AEROSPACE MEDICINE Hyperbaric Medicine Div, Brooks AFB, TX

USCG (G-MP-3 USP 82) Washington Dc; (Smith), Washington, DC; G-EOE-2 61 (Espinshade), Washington, DC; G-EOE-4 (T Dowd), Washington, DC; G-MMT-4 82 (J Spencer); Gulf Strike Team, Bay St. Louis, MS; Lant Strike Team Elizabeth City, NC; Oceanographic Unit Technical Ref Sect, Washington, DC; Pac Strike Team, Hamilton AFB, CA

USCG R&D CENTER CO Groton, CT; D. Motherway, Groton CT; D. Paskausky, Groton, CT; Debok, Avery Point, CT; S Rosenberg, Groton, CT

USDA Forest Products Lab, Madison WI; Forest Products Lab, (R. DeGroot), Madison WI; Forest Service Reg 3 (R. Brown) Albuquerque, NM; Forest Service, Bowers, Atlanta, GA; Forest Service, San Dimas, CA

USGS Gregory, Reston, VA

USNA Ch. Mech. Engr. Dept Annapolis MD; ENGRNG Div, PWD, Annapolis MD; Energy-Environ Study Grp, Annapolis, MD; Environ. Prot. R&D Prog. (J. Williams), Annapolis MD; Mech. Engr. Dept. (C. Wu), Annapolis MD; PWO Annapolis MD; USNA SYS ENG DEPT ANNAPOLIS MD

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9 Structural analysis and design (including numerical and computer techniques)
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